Published Papers Using NOKOV Motion Capture System

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Part I Robotics & Engineering

I. UAV/UGV

17-Point Algorithm Revisited: Toward a More Accurate Way

Abstract

17-point algorithm is a popular method in relative pose estimation of multi-cameras. However, the role of overlap in 17-point algorithm remains unexplored. And the relaxed way in solving constrained normal equation leads to sub-optimal results. Both of them influence accuracy of the estimated pose. In this paper, we theoretically analyze the influence of overlap and the solvability of 17-point algorithm. In addition, we show that the abuse of overlap can harm accuracy in practice. In light of these findings, we propose an improved 17-point algorithm, which avoids using overlaps and derives a simple way to solve normal equation on manifold. Both simulations and real world data experiments demonstrate the proposed one outperforms the traditional 17-point algorithm in term of accuracy.

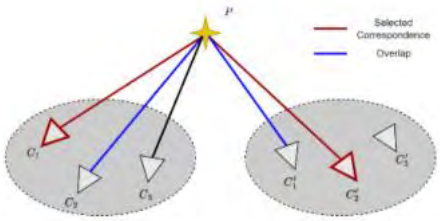

Fig. 1: An example to illustrate the concept of overlap, which denotes for the extra correspondence.

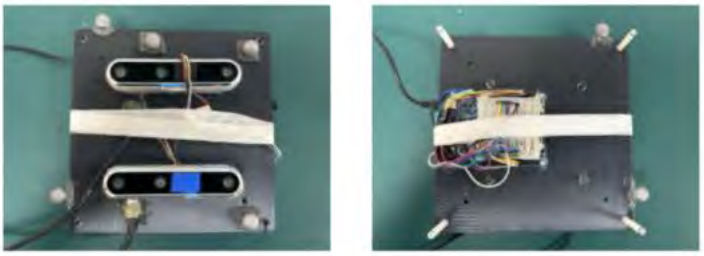

Fig. 8: Customized, synchronized multi-camera rig.

How NOKOV Contributes to the Research

We employ a frame-to-frame matching within a NOKOV motion capture-enabled environment which can provide the ground truth pose.

Citation C. Xie, R. Xing, N. Hao and F. He, "17-Point Algorithm Revisited: Toward a More Accurate Way," 2024 IEEE International Conference on Robotics and Automation (ICRA), Yokohama, Japan, 2024, pp. 10208-10214, doi: 10.1109/ICRA57147.2024.10611149.

Link https://ieeexplore.ieee.org/document/10611149

A Collaborative Stereo Camera with Two UAVs for Long-distance Mapping of Urban Buildings

Keywords

Visualization, Parameter estimation, Navigation, Buildings, Semantics, Robot vision systems, Collaboration, Cameras, Autonomous aerial vehicles, Real-time systems

Abstract

For a swarm of Unmanned Aerial Vehicle (UAV), long-distance visual mapping is advantageous for pre-planning navigation paths in unknown urban building environments. This work leverages two cameras on two UAVs to build a wide baseline collaborative stereo camera, which can construct a navigable mesh map for remote building obstacles. We present a complete framework of the collaborative stereo camera for long-distance mapping, including online extrinsic parameter estimation of the stereo camera, real-time cross-camera feature association, and semantic mesh map generation of remote build ings. Extensive simulations and real-world experiments verify the effectiveness of the collaborative stereo camera. With a 3m baseline, the collaborative stereo camera achieves long-distance mapping of buildings (20m ~ 50m) away with a relative error of approximately 10%. The constructed remote map enables UAVs to pre-detect large obstacles and pre-plan navigation paths in large-scale building environments. Hopefully, this work can provide a novel and practical approach for collaborative visual tasks of UAV swarm.

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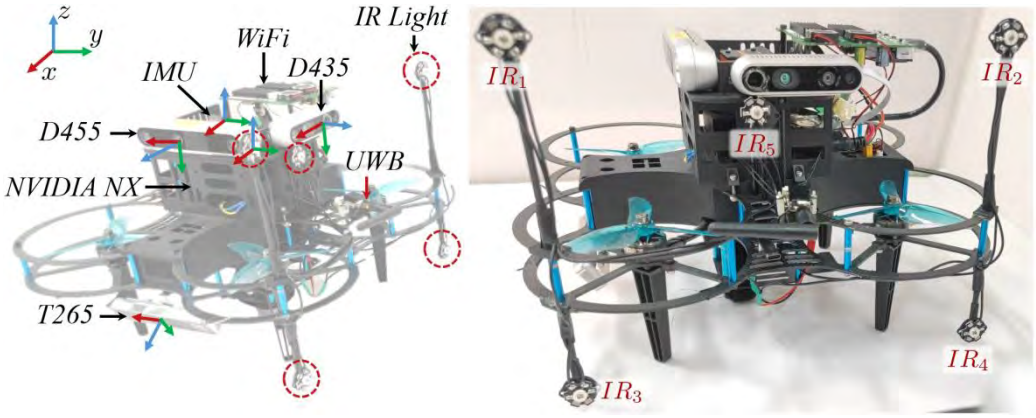

How NOKOV Contributes to the Research

The evaluation of the extrinsic parameter estimation of the stereo camera is performed under the NOKOV motion capture system.

Citation Wang Z, Dong W. A Collaborative Stereo Camera with Two UAVs for Long-distance Mapping of Urban Buildings[C]//2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2024: 7944-7951.

Link https://ieeexplore.ieee.org/document/10801758

A cross-platform deep reinforcement learning model for autonomous navigation without global information in different scenes

Keywords

Deep reinforcement learning, Intelligent transportation system, Autonomous navigation, Neural networks

Abstract

This paper employs a deep reinforcement learning algorithm named Twin Delayed Deep Deterministic algorithm into autonomous navigation in intelligent transportation systems. It trains a fully connected neural network model in a simulation environment, which outputs the expected linear and angular velocity of the vehicle based on real-time data measured by embedded sensors. Through continuous epochs of training, the model gradually navigates the vehicle to reach a provided destination by making rational motion decisions at each discrete time instant without knowing global environment information. Especially, to improve the model's generalization ability across various scenes, an input preprocessing function is proposed to eliminate the singularity and uniformity of raw input data. A large number of simulation tests are carried out, where the proportion that the vehicle moves from a start position to a destination without collision within a specified limited time exceeds 90%. The remaining failures are mainly due to the vehicle's inability to approach the destination immediately adjacent to obstacles for its safety. Furthermore, traditional mapless navigation algorithms suffer from locally optimal solutions in the face of U-shaped obstacles. This paper introduces a virtual obstacle mechanism designed to prevent the vehicle from entering the U-shaped region, effectively addressing the aforementioned issue. Finally, the model trained from the simulation environment can be directly loaded onto a physical vehicle without considering the different processor architectures. Large quantities of experiments show that the model improves the autonomous navigation capability of vehicles when global environment information cannot be obtained by the system, which optimizes the functions of the navigation module in intelligent transportation systems.

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(a) Platform panorama

(b) Navigation scene (c) Robot

Fig. 9. A physical platform composed of obstacles, vehicles and positioning devices is built to test the actual navigation performance of the trained model.

How NOKOV Contributes to the Research

A 4 m×4 m navigation field, as shown in Fig. 9 is constructed to test the autonomous navigation capability of a vehicle loaded with our trained model. The field contains randomly placed cardboard boxes that serve as obstacles. To accurately obtain the real-time pose of the vehicle, a set of motion capture device developed by Nokov Science & Technology Co., Ltd is equipped in the field. The device provides sub millimeter positioning accuracy and its data can be read by various terminals.

Citation Chuanxin Cheng, Hao Zhang, Yuan Sun, Hongfeng Tao, Yiyang Chen,A cross-platform deep reinforcement learning model for autonomous navigation without global information in different scenes,Control Engineering Practice,Volume 150,2024,105991,ISSN 0967-0661,https://doi.org/10.1016/j.conengprac.2024.105991.

Link https://www.sciencedirect.com/science/article/abs/pii/S0967066124001515

A Deep Reinforcement Learning Approach Combined With Model-Based Paradigms for Multiagent Formation Control With Collision Avoidance

Keywords

Collision avoidance, combined model-based and data-driven, deep reinforcement learning (DRL), formation control, multiagent system (MAS)

Abstract

Generating collision-free formation control strategy for multiagent systems faces huge challenges in collaborative navigation tasks, especially in a highly dynamic and uncertain environment. Two typical methodologies for solving this problem are the conventional model-based paradigm and the data-driven paradigm, particularly the widely used deep reinforcement learning (DRL) method. However, both the model-based and data-driven paradigms encounter inherent drawbacks. In this paper, we present two novel general schemes that combine these two paradigms together in an online mode. Specifically, the two paradigms are combined in a parallel and a serial structure in these two schemes, respectively. In the parallel scheme, the outputs of the model-based and DRL-based controllers are lumped together. In the serial scheme, the output of the model-based controller is fed as an input of the DRL-based controller. The interpretation of the two combined schemes is suggested from a control-oriented perspective, where the parallel DRL controller is viewed as a complementary uncertainty compensator and the serial DRL controller is taken as an inverse dynamics estimator. Finally, comprehensive simulations are conducted to demonstrate the superiority of the proposed schemes, and the effectiveness is further verified by deploying our schemes to a physical experiment platform based on a set of three-wheeled omnidirectional robots.

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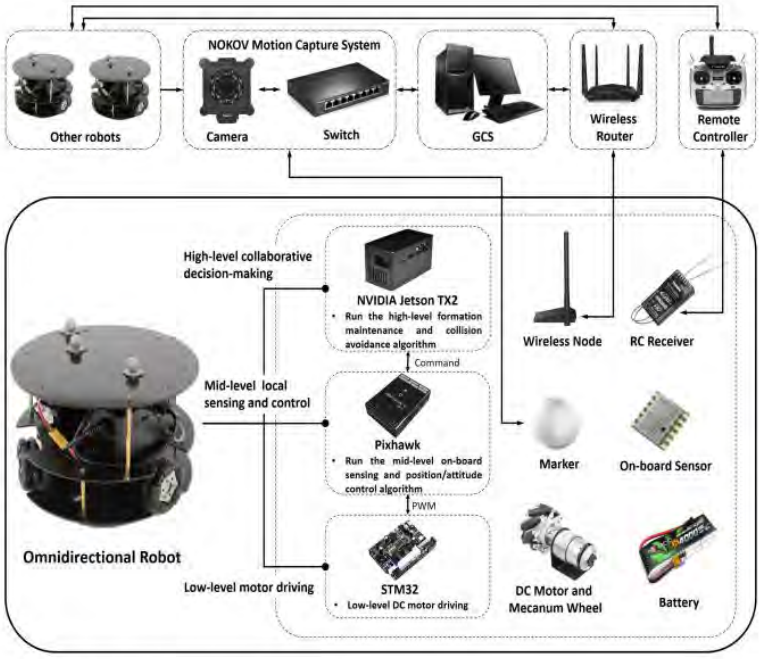

Fig. 10. Hardware structure of the omnidirectional robot platform.

How NOKOV Contributes to the Research

TheNOKOVmotion capture system (https\://www\.nokov.com/) is adopted as the indoor positioning system which can provide millimeter-level position measurement.
A ground control station (GCS) connected with theNOKOVsystem and the wireless router serves as the central management system.

Citation Pu Z, Zhang T, Ai X, et al. A deep reinforcement learning approach combined with model-based paradigms for multiagent formation control with collision avoidance[J]. IEEE Transactions on Systems, Man, and Cybernetics: Systems, 2023, 53(7): 4189-4204.

Link https://ieeexplore.ieee.org/document/10047984

A Deep Reinforcement Learning Approach Using Asymmetric Self-Play for Robust Multirobot Flocking

Keywords

Adversarial training, flocking, multiagent deep reinforcement learning (MADRL), autonomous vehicles.

Abstract

Flocking control, as an essential approach for survivable navigation of multirobot systems, has been widely applied in fields, such as logistics, service delivery, and search and rescue. However, realistic environments are typically complex, dynamic, and even aggressive, posing considerable threats to the safety of flocking robots. In this article, based on deep reinforcement learning, an Asymmetric Self-play-empowered Flocking Control framework is proposed to address this concern. Specifically, the flocking robots are trained concurrently with learnable adversarial interferers to stimulate the intelligence of the flocking strategy. A two-stage self-play training paradigm is developed to improve the robustness and generalization of the model. Furthermore, an auxiliary training module regarding the learning of transition dynamics is designed, dramatically enhancing the adaptability to environmental uncertainties. Feature-level and agent-level attention are implemented for action and value generation, respectively. Both extensive comparative experiments and real-world deployment demonstrate the superiority and practicality of the proposed framework.

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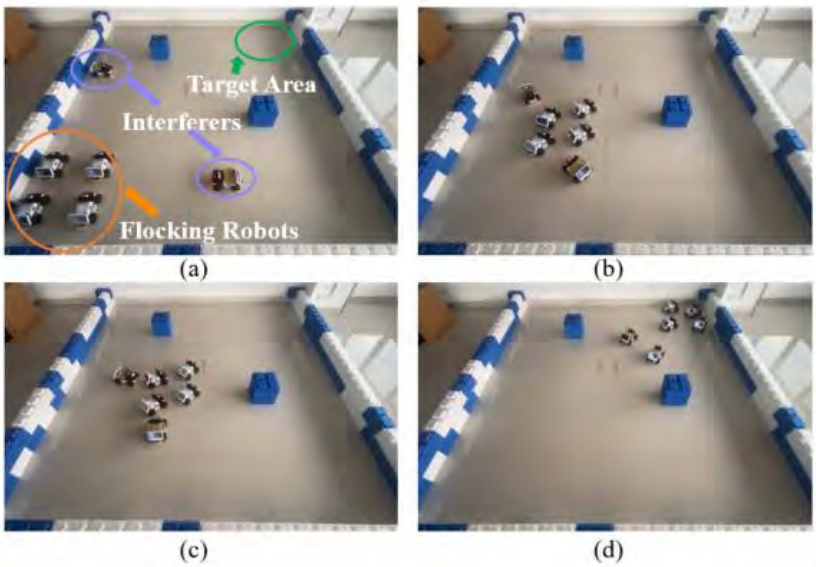

Fig. 11. Snapshots of four flocking robots adopting ASFC and two heuristic adversarial interferers. A video about the physical experiment is available at https://youtu.be/Kn3ssyrA3uE. (a) Robots in the starting area; (b) Robots navigating towards the target; (c) Robots avoiding interference; (d) Robots reaching the target.

How NOKOV Contributes to the Research

In addition to simulations, the proposed ASFC method is deployed on physical robots to validate its practicality. We set up a 4 m × 4 m area with four robots, two interferers, and two static obstacles. AgileX LIMO mobile robots and NOKOV Motion Capture are used. The ASFC policy developed in simulations guided the robots. A wireless communication system comprising a router connects robots as mobile nodes to a control station. The control station acts as a data transceiver, receiving data from robots, calculating actions, and transmitting them back. The model is run on this platform, and its performance is captured by a camera, with key snapshots shown in Fig. 11, where robots successfully evade interference and maintain flocking to the target. Each computation cycle takes 2.25 ms, well below the 200 ms decision interval, demonstrating the system's real-time capability.

Citation Jia Y, Song Y, Cheng J, et al. A Deep Reinforcement Learning Approach Using Asymmetric Self-Play for Robust Multirobot Flocking[J]. IEEE Transactions on Industrial Informatics, 2025.

Link https://ieeexplore.ieee.org/document/10851371

A Diffusion-Based Multi-Objective Ant Colony Algorithm for Optimizing Network Topology Design

Keywords

diffusion mechanism, multi-objective ant colony optimization, network topology construction

Abstract

Network topology construction is critical for designing efficient and resilient networks. Although ant colony optimization (ACO) has been widely applied in these tasks owing to its advantage of the pheromone update mechanism, it still exhibits limitations in solving such multi-objective optimization problems and converges slowly. This paper proposes a Diffusion-Based Multi-Objective Ant Colony Optimization (DMAC) algorithm for effective and reliable network topology construction. DMAC integrates pheromone diffusion mechanisms with multi-objective ACO to optimize multiple critical objectives concurrently and accelerate convergence. Experiments on simulation and real-world implementation demonstrate DMAC's ability to construct high-quality topologies balancing key tradeoffs within a small iteration budget. The proposed combination of diffusion mechanisms and multi-objective ACO addresses the limitations of prior ACO methods and provides new effective approach to automated network topology construction under multiple design constraints. DMAC demonstrates promising performance improvements on this complex multi-objective optimization problem and has great application potential in other fields and algorithms.

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Figure 5: Experimental site and Tianbot Mini swarm (left), Nokov motion capture system capturing the position information of the vehicles (right) .

How NOKOV Contributes to the Research

NOKOV Motion Capture System: NOKOV motion capture system is produced by NOKOV Science & Technology. The systemuses a high-performance infrared camera (12MP resolution and 300Hz capture frequency) to locate the position of a set of reflectivemarkers and builds 3D motion data through its analysis system.And the location information of markers can be obtained in realtime in the ROS system.

Citation Hu H, Zhang H, Shi E, et al. A Diffusion-Based Multi-Objective Ant Colony Algorithm for Optimizing Network Topology Design[C]//Proceedings of the 2023 9th International Conference on Communication and Information Processing. 2023: 393-399.

Link https://dl.acm.org/doi/abs/10.1145/3638884.3638945

A Dual Closed-loop Control Scheme for Quadrotor under Disturbances

Keywords

Active disturbance rejection control, Extended state observer, Motor dynamics, Position and attitude control, Quadrotor

Abstract

In this paper, a double closed-loop control scheme based on active disturbance rejection control (ADRC) is proposed to enhance the anti-disturbance ability and trajectory tracking accuracy of the quadrotor unmanned aerial vehicle (UAV) system. Firstly, quadrotor's dynamic model is established and simplified. Secondly, the corresponding active disturbance rejection controller is designed for attitude inner loop and position outer loop respectively, the extended state observer (ESO) considering the motor dynamics which makes the observation more accurate is used to estimate and compensate the internal uncertainties and external disturbances in real-time. The experimental results show that the control scheme proposed in this paper can largely ensure that the quadrotor tracks the target trajectory quickly and accurately while maintaining stability, even with intense external disturbances.

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(a) (b)

Fig. 3. (a) Experimental platform. (b) Experiment with disturbances.

How NOKOV Contributes to the Research

In this section, the proposed method is verified via ex-periments. As shown in Fig. 3(a), the quadrotor for theexperiments is built on basis of QAV-250 frame and ANO-Pioneer flight control board. The attitude measurements areobtained from an on-board ICM20602 IMU module. The position measurements are obtained from the Nokov motion capture system.

Citation Hao C, Xia Y, Ma D, et al. A dual closed-loop control scheme for quadrotor under disturbances[C]//2019 IEEE International Conference on Unmanned Systems (ICUS). IEEE, 2019: 877-882.

Link https://ieeexplore.ieee.org/abstract/document/8995953

A Fast Switching-based Trajectory Planning Algorithm for Aggressive Quadrotor Flight

Keywords

motion and path planning, graph search, autonomous vehicle navigation, quadrotor

Abstract

In this paper, an online trajectory planning problem is investigated for aggressive quadrotor flight in cluttered environments with multi-form narrow gaps. An efficient planning framework is developed, in which a switching policy is designed to choose planning methods based on the obstacle information. First, we propose the Guide State Set (GSS) generating algorithm to derive feasible states from the narrow free space (NFS). Next, the initial path is obtained using the generated GSSs: When the search process is near a GSS, a guide trajectory with an expected final state is generated to prevent the aimless expansions. If the current state is away from all GSSs, the graph search method is applied with a lazy checking strategy to speed up searching. Finally, the proposed method is validated by simulation and experimental results.

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(a) (b) (c)

Fig. 7: snapshots of the video shows the attitude change of the quadrotor while flying through a narrow gap.

How NOKOV Contributes to the Research

We also use a NOKOV motion capture system for localization.The global map is built in advance using an Intel Realsense-D435i depth camera. To demonstrate the possibility of online planning, we restrict the global map to a sphere centeredon the quadrotor with a radius of 3 m. With a replanning fre-quency of 2 Hz, the quadrotor is able to pass through the gap with a maximum speed of 1.18 m/s.

Citation Gao J, Yao H, Cao H, et al. A Fast Switching-based Trajectory Planning Algorithm for Aggressive Quadrotor Flight[C]//2022 41st Chinese Control Conference (CCC). IEEE, 2022: 3846-3851.

Link https://ieeexplore.ieee.org/abstract/document/9902454

A Feedback Linearization and Saturated Control Structure for Quadrotor UAV

Keywords

UAV, Feedback linearization control, LESO

Abstract

In this paper, attitude controller and position controller are investigated for a small quadrotor unmanned aerial vehicle (UAV). A feedback linearization method is proposed to design attitude tracking control of UAV, with linear extended state observer (LESO) to estimate and compensate for the disturbances. Meanwhile, a saturated control law with arc tangent functions is adopted as the position controller. Then the convergence of LESO, stability of attitude system and position system are proved. Finally, experiment results are given to illustrate the effectiveness of the proposed method.

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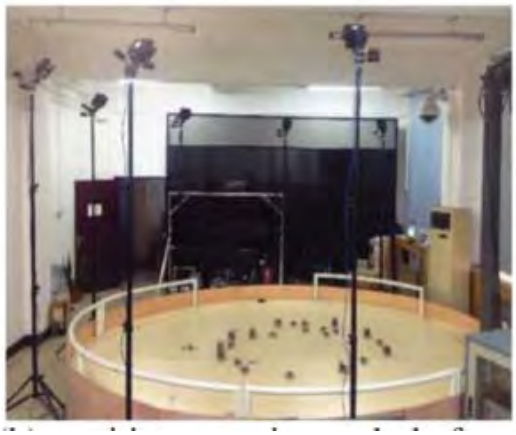

How NOKOV Contributes to the Research

The quadrotor position experimental platform is shown in Fig.3b, which exits three parts: Nokovmotion capture sys- tem, quadrotors and communication system. Nokovmotion capture system gets the position of the quadrotor byNokovmarkers (reflective balls), the quadrotor can get the informa- tion of its own precise position via communication system (WiFi). Based on the quadrotor position experimental plat- form, a hovering test is done to verify the effectiveness of position system control. The parameters of position system are given in Table.2. In this case, the experimental results are shown in Fig.6 and Fig.7. Fig.6 shows the position tracking performance and Fig.5 shows the inputs of position system. From results, the errors of position from x and y axes are less than 0.1 meter and inputs are reasonable. In other word, it can accurately track the reference position.

Citation Jiang H, Xia Y, Hu R, et al. A feedback linearization and saturated control structure for quadrotor UAV[C]//2019 Chinese Control Conference (CCC). IEEE, 2019: 8277-8282.

Link https://ieeexplore.ieee.org/abstract/document/8866172

A GCN-GRU-KAN-Based Framework for UWB 3D localization in adverse geometric configurations

Keywords

Ultra Wide Band, Geometric configuration, Deep learning, 3D positioning

Abstract

This study addressed the challenge of three-dimensional (3D) positioning using an ultra-wide band (UWB) in environments with poor geometric configurations of base stations. To improve the positioning accuracy in narrow spaces and with limited base station deployment, a deep learning model combining Graph Convolutional Networks (GCN), Gate Recurrent Units (GRU), and Kolmogorov-Arnold Networks (KAN) was proposed. The GCN extracted the spatial structural features, the GRU captured the temporal sequence information, and the KAN adaptively integrated the key features to further enhance accuracy. The experimental results indicated that introducing a GCN reduced the positioning error by 43.0 %–50.6 % and the standard deviation by 24.2 %–43.3 %, compared to Convolutional Neural Networks (CNN). Compared to the fully connected layers, KAN reduced the positioning error by 30.4 %–62.2 % and the standard deviation by 6.0 %–61.3 %. The model achieved an average positioning error of less than 10 cm, with accuracy improvements of 22.2 %–76.1 %, surpassing the traditional methods and other deep learning algorithms, and demonstrating exceptional robustness and adaptability.

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Fig. 6. Air-raid Shelter Scenario.

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4.Experiments
To achieve 3D localization in environments with poor base stationgeometric configurations, such as narrow mine shafts, and to better alignwith practical application scenarios, experiments were conducted in anair-raid shelter resembling a mine environment. The experimental setupis illustrated in Fig. 6.
The equipment used in this experiment was categorized into twoparts. The hardware for obtaining the ground truth included NOKOV'sMARS2H and MARS9H motion capture cameras, as shown in the bluebox, and the software used was "XINGYING". The cameras were con-nected via Ethernet cables, enabling the real-time acquisition of thecaptured object's 3D position with an overall system accuracy of + 0.15mm, meeting the ground truth requirements. The positioning experi-ment involved five DWM1000 UWB devices,

Citation Wang P, Lian Z, Núñez-Andrés M A, et al. A GCN-GRU-KAN-Based Framework for UWB 3D localization in adverse geometric configurations[J]. Measurement, 2025: 119066.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001578792300003

A modified fruit fly optimization algorithm to active disturbance rejection control parameters tuning for trajectory tracking of omnidirectional mobile robotic chassis

Keywords

Omnidirectional mobile robotic chassis, Linear active disturbance rejection controller, Fruit fly optimization algorithm Levy flight, Opposition-based learning

Abstract

To achieve the more effective and robust trajectory tracking performance for the omnidirectional mobile robotic chassis (OMRC), a control system is designed by combining the linear active disturbance rejection control (LADRC) and proportional-integral-derivative (PID) methods, while a novel modified fruit fly optimization algorithm (Le-OFFO) is proposed to achieve the optimal parameters for the designed controller. The PID controller is utilized to the outer loop for trajectory tracking and LADRC controller is applied to the inner loop for the control of torque of each motor. A fitness function is established to evaluate the cost of control system, with several metrics and constraints taking into consideration. The proposed Le-OFFO algorithm combines the levy flight and the opposition-based learning (OBL) operators, in which the levy flight can help to escape from local optimum and the OBL-based mutation operator can enhance the exploration ability. The optimal parameters combination for the designed control system can be achieved by using the Le-OFFO to minimize the objective function. Numerous results show that the Le-OFFO has better performance of convergence speed and exploitation capability compared with other optimization algorithms in solving the controller parameter tuning problem. In addition, the effectiveness of the optimized LADRC controller is validated by results of experiments when compared with basic PID controller and original ADRC controller.

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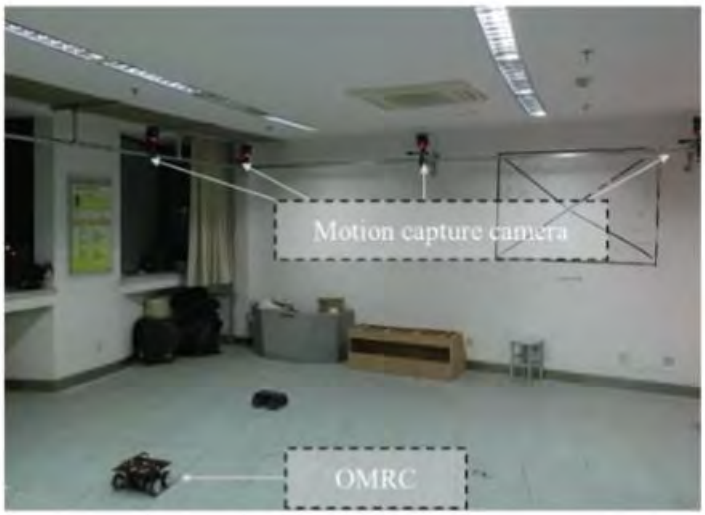

Fig. 17 The experiment environment

How NOKOV Contributes to the Research

5.4 Experiments in real scenario
In this section, experiments in real scenario are carried outto test the performance of the proposed control framework,As shown in Fig.17, the experiment platform consists of NOKOV motion capture system, ground station andOMRC. The relationship of hardware is shown in Fig. 18.Specifically, the motion capture system is used to locate theposition of OMRC. The proposed control framework isdeployed on microcontroller unit (MCU). The ground sta-tion is used to send the reference trajectory to the OMRC.

Citation Zhang X, Wu W, Li X. A modified fruit fly optimization algorithm to active disturbance rejection control parameters tuning for trajectory tracking of omnidirectional mobile robotic chassis: X. Zhang et al[J]. Soft Computing, 2025: 1-21.

Link https://link.springer.com/article/10.1007/s00500-025-10638-4

A Region-Based Relay Pursuit Scheme for a Pursuit–Evasion Game With Curvature-Bound Players

Keywords

Curvature constraint, multiagent systems, relay pursuit, pursuit–evasion game

Abstract

In this article, the problem of the relay pursuit–evasion game is investigated. The game involves multiple pursuers and a single evader, which are all subject to the constraint of bounded curvature. To solve this problem, we develop a novel relay pursuit scheme that allows the single evader to be captured by the pursuers. First, the round pursuit strategy is derived as an alternative strategy to the circle straight pursuit strategy to further unlock the capture potential of the static pursuers. Next, the planar space is partitioned into some separate dominance regions by comparing the capture times required for each pursuit strategy. In consequence, a relay pursuit scheme based on the dominance region is obtained. At the end, a set of experiment results are presented to reveal the practicality and superiority of the approach developed in this article.

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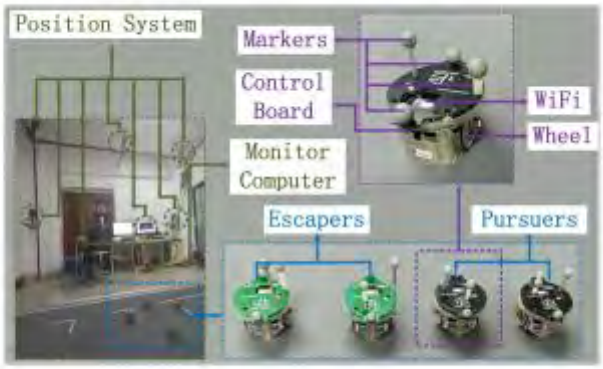

Fig. 3. Wheeled mobile robots platform.

How NOKOV Contributes to the Research

In this section, several experiments are conducted on thewheeled mobile robots platform to demonstrate the performanceof the presented algorithm. The composition of the experimentplatform is shown in Fig.3. There is a set of wheeled mobile robots (E-puck2) and a position system (Nokov, Mars 2H),which contains two monitor computers (Lenovo savior blade7000) and twelve cameras (2.2 megapixel, 380 Hz frame rate).

Citation Pan T, Yuan Y, Wang Z, et al. A Region-Based Relay Pursuit Scheme for a Pursuit–Evasion Game With Curvature-Bound Players[J]. IEEE Transactions on Industrial Electronics, 2024, 71(12): 16308-16316.

Link https://ieeexplore.ieee.org/abstract/document/10535755

A Safety Modulator Actor-Critic Method in Model-Free Safe Reinforcement Learning and Application in UAV Hovering

Keywords

Distributional critic, Overestimation mitigation, Safe reinforcement learning, Safety modulator

Abstract

This paper proposes a safety modulator actor-critic (SMAC) method to address safety constraint and over-estimation mitigation in model-free safe reinforcement learning (RL). A safety modulator is developed to satisfy safety constraints by modulating actions, allowing the policy to ignore safety constraint and focus on maximizing reward. Additionally, a distributional critic with a theoretical update rule for SMAC is proposed to mitigate the overestimation of Q-values with safety constraints. Both simulation and real-world scenarios experiments on A Safety-Adjusted Policy Optimization Algorithm and Application for Obstacle Avoidance in the QuadcopterUnmanned Aerial Vehicles (UAVs) hovering and figure-8 tracking confirm that the SMAC can effectively maintain safety constraints and outperform mainstream baseline algorithms.

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Figure 6: The Crazyflie 2.1 hovering at 1.5m height in real-world.

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6.3. Real-World Experiment
With the help of precise simulation models of PyBullet, the UAV hovering and figure-8 tracking taskscan be easily deployed to the Crazyflie 2.1 in real-world as shown in Figure 6 and 8. In real-world ex-periments, position and orientation information, such as Euler angles, are primarily calculated based on NOKOV Motion Capture System.

Citation Qi Q, Yang X, Xia G, et al. A Safety Modulator Actor-Critic Method in Model-Free Safe Reinforcement Learning and Application in UAV Hovering[J]. arXiv preprint arXiv:2410.06847, 2024.

Link https://wos.vntr.top/wos/woscc/full-record/WOS:001606435800001

A Safety-Adjusted Policy Optimization Algorithm and Application for Obstacle Avoidance in the Quadcopter

Abstract

Ensuring the safety of various real-world applications based on reinforcement learning (RL), such as quadcopter control, robotic manipulators, and autonomous robots, remains a critical challenge, despite RL's remarkable success in solving complex decision-making tasks. Existing on-policy Lagrangian optimization methods in safe RL typically use a single policy to balance the trade-off between safety and return without taking the potential benefits of adopting multiple policies into account. In this paper, a new on-policy method is proposed, named Safe-Adjusted Policy Optimization(SAPO), which is a dual-policy framework designed to address safety constraint violations in RL. By incorporating a cost-oriented policy to dynamically adjust a reward-oriented policy, the SAPO effectively resolves the trade-off between safety and return. Moreover, to enhance performance in carrying out high-dimensional tasks, the Kullback-Leibler (KL) divergence and a Gaussian kernel are employed in the distance functions to facilitate the training. In addition, a quadcopter-safe-navigation task is designed to overcome the drawback of previous research on quadcopter-safe-navigation with RL that only pays attention to reward function design without considering policy-level optimization. Finally, experimental results verify the feasibility of the designed task. Meanwhile, indicated by the test on real device, the proposed algorithm is easy to be implemented, offers performance guarantees, and outperforms existing safe RL baselines.

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Fig. 7: The real-world experiment.

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In the real-world experiment, Crazyflie 2.1 is used withall its states captured using the NOKOV motion capturesystem. Additionally, the low-level control of Crazyflie 2.1 ismanaged through the Crazyswarm platform [40], and virtualobstacles are represented by physical spheres created byusing 3D printing. As shown in the Fig. 7, the quadrotorsuccessfully completes the task in the real-world environ-ment with fluid flight performance. Overall, the sim-to-realexperiment demonstrates that the SAPO algorithm not onlymaintains its safety guarantees but also achieves a high returnin the real-world scenario.

Citation G. Xia, X. Yang, Q. Qi, Y. Sun and X. Dong, "A Safety-Adjusted Policy Optimization Algorithm and Application for Obstacle Avoidance in the Quadcopter," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 2360-2367, doi: 10.1109/IROS60139.2025.11247653.

Link https://ieeexplore.ieee.org/document/11247653

A swarm model with constraint coordination mechanism for unmanned aerial vehicle swarm formation maintenance in dense environments

Keywords

Formation maintenance, Constraint coordination, Self-organized behavior, UAV swarm

Abstract

Purpose: The formation of unmanned aerial vehicle (UAV) swarm plays a critical role in numerous applications, such as unmanned agriculture, environmental monitoring and cooperative fencing. Meanwhile, the self-organized swarm model exhibits excellent performance in amorphous formation flight, and its collective motion pattern displays great potential in dense obstacle avoidance. The paper aims to realize the formation maintenance of UAVs while combining the advantage of the self-organized swarm model in avoiding dense obstacles. Thereby enhancing the flexibility, adaptability and safety of UAV swarms in dense and unpredictable scenarios.

Design/methodology/approach: In this paper, a self-organized formation (SOF) swarm model with a constrained coordination mechanism is proposed. A global information-based formation rule is designed to flexibly maintain the formation. A constraint coordination mechanism is designed to resolve the problem of constraint conflicts between formation rules and self-organized behavior rules. The model introduces a new obstacle avoidance rule to prevent deadlocks. Extensive experiments including simulations, real flights and comparative experiments are conducted to evaluate the performance of the model.

Findings: The simulation results show that SOF swarm enables the formation elastically to dense obstacles. Compared to the Vasarhelyi model, swarm performance metrics are improved. For example, the task completion time of SOF swarm is reduced by 16%, 28% and 39% across the three obstacle densities, and the order of SOF swarm is improved by 4%, 13% and 18%, respectively. The proposed model is also validated with a swarm of seven quadcopters that can successfully navigate and maintain formation in a real-world indoor environment with dense obstacles. Video at: https\://youtu.be/V8hYgOHxWls.

Research limitations/implications: The proposed formation rule is based on global information construction, which presents challenges in terms of communication overhead in distributed systems.

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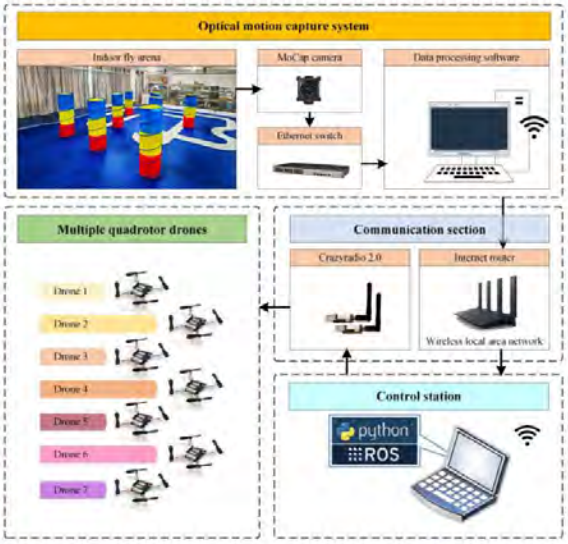
Originality/value: An SOF swarm model is proposed, which achieves formation maintenance by incorporating formation rule and constraint coordination mechanism and improves obstacle avoidance performance by introducing a new obstacle avoidance rule. After real UAVs verification, the model is feasible for practical deployment and provides a new solution to the formation flight and formation maintenance problems encountered in dense environments.

Figure 4 Self-organized UAV swarm flight experimental platform



Notes: The platform consists of optical motion capture system, communication section, control station and multiple quadrotor drones
Source: Authors own work

How NOKOV Contributes to the Research

The self-organized UAV swarm flight experiment platform is shown in Figure 4, which includes theNOKOVMotion Capture System, the Robot Operating System, a Wireless Local Area Network, a pair of UAV communication modules and a set of quadcopters. The motion capture system consists of sixteen motion capture cameras, an ethernet switch and data processing software. The cameras are evenly distributed on top of the frame, and they capture the state of the UAV in real-time by tracking the marker balls that are attached to the UAV.

Citation Xiong H, Shi X, Liu J Z, et al. A swarm model with constraint coordination mechanism for unmanned aerial vehicle swarm formation maintenance in dense environments[J]. Industrial Robot: the international journal of robotics research and application, 2024.

Link https://www.emerald.com/insight/content/doi/10.1108/ir-07-2024-0316/full/html

A Trajectory-based Flight Assistive System for Novice Pilots in Drone Racing Scenario

Keywords

Codes,Trajectory,Planning,Robotics and automation,Drones

Abstract

Drone racing has become a popular international competition and has attained wide attention in recent years. However, the requirements of high-level operation keep the novice pilots away from participating in it. This paper presents a trajectory-based flight assistive system that enables various operators to fly the drone in a racing scene at a high speed. The whole system is structured hierarchically, consisting of both offline and online components. In the offline part, a global time-optimal trajectory is generated as the expert reference, and a dense flight corridor is constructed to provide sufficiently large safe region. In the online part, a remote control-mapped primitive is designed to fast encapsulate pilots' inputs, and the time mapping based trajectory progress is customized to further capture intention. Then, a trajectory planner is proposed to generate intention-aligned, smooth, feasible, and safe trajectories periodically. Additionally, a yaw planning that provides the pilot with the best suitable view angle is employed to further alleviate the operation difficulty. Simulations and real world experiments are implemented to verify the performance of our system. The maximum flight speed can reach 6.0 m/s for a novice drone pilot in a real racing scene. Our code is released as an open-source package.

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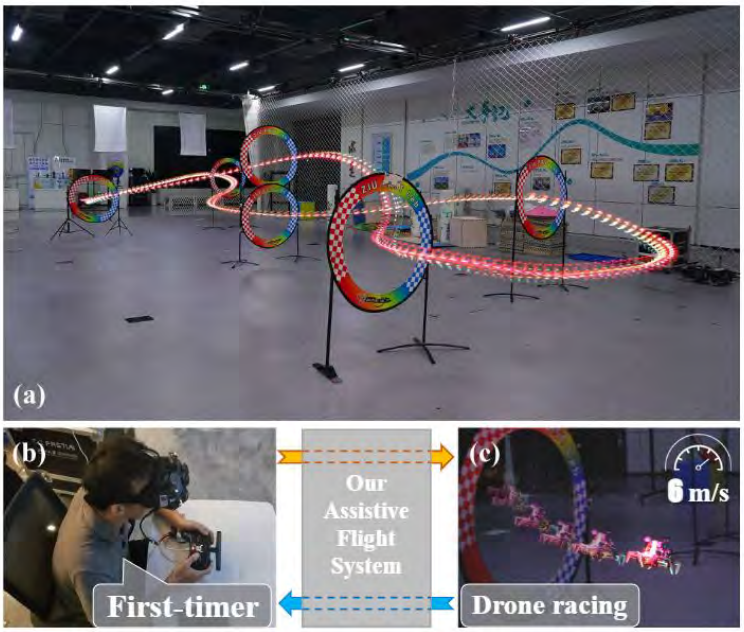

Fig. 1. Illustration of the real world experiments of our flight assistive system in a racing scene. (a) The demonstration of the real drone racing performance. (b) The first-time flying pilot wears goggles to access the FPV and operates the joystick to control the drone. (c) The snapshot of the racing drone at a high flight speed.

How NOKOV Contributes to the Research

The localization of drones is achieved by motion capture system.

Citation Y. Zhong, G. Zhao, Q. Wang, G. Xu, C. Xu and F. Gao, "A Trajectory-based Flight Assistive System for Novice Pilots in Drone Racing Scenario," 2024 IEEE International Conference on Robotics and Automation (ICRA), Yokohama, Japan, 2024, pp. 8714-8720, doi: 10.1109/ICRA57147.2024.10610179.

Link https://ieeexplore.ieee.org/document/10610179

A Two-Stage Swarm Planning Framework for Efficient Multi-DroneWaypoint Traversal

Keywords

Multi-drone waypoint traversal, Trajectoryplanning, Distributed planning, Voronoi diagrams

Abstract

The multi-drone waypoint traversal has significant potential for aerial robot swarms in various applications. However, it still faces challenges including low time efficiency, susceptibility to local minima, poor resilience to external disturbances, high computational complexity, and high communication burden. To address these issues, we propose a two-stage swarm planning framework by integrating an offline global trajectory generator and an online distributed local trajectory planner. This approach not only ensures time-optimality but also enhances resistance to external disturbances. Specifically, a complementary progress constraint (CPC)-based global trajectory planning method is first presented to generate globally optimal reference trajectories. Then, by taking these trajectories as global guidance, a local planner is designed to guarantee collision-free traversal. In the local planner, we present a distributed local re-planning algorithm by embedding the positional constraints constructed by Voronoi diagrams into the model predictive contouring control (MPCC). The drones only exchange their position information, significantly reducing the communication load. Additionally, the Voronoi-based spatial constraints allow the swarms to eliminate the collision risk caused by asynchronous communication. To reduce onboard computational resource requirements, the local planner adopts the real-time iteration (RTI) technique, executing the optimization only once per control cycle. Both simulation and real-world experiments demonstrate that our approach outperforms state-of-the-art methods in terms of waypoint tracking accuracy, safety, and global time optimality.

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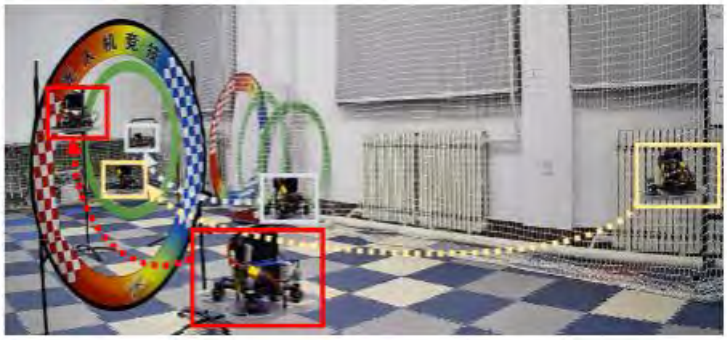

Fig. 8. The drone swarm is performing the waypoint traversal task.

How NOKOV Contributes to the Research

The software architecture of the system is presented next. First, ws use the algorithm described in Subsection II-B,the optimal trajectory is generated offline by pre-providingthe waypoint information and then assigned to each drone.This algorithm is written in Python and utilizes the CasADisolver for computation. Next, the drones use the obtained trajectory as a reference trajectory and apply the algorithmfrom Subsection II-C to compute the desired acceleration commands for the flight controller to execute. This algorithmruns in real-time on the onboard computer and is written inC++ using the ROS framework. The OSQP solver \[17] isused to solve the optimization problem, and the planning frequency is 20Hz. The position and velocity information of each drone is provided by the motion capture system and the EKF module of the flight controller, while the positions ofother drones are provided by the NOKOV Motion Capture System. The

Citation K. Cui, F. He, N. Hao and H. Hu, "A Two-Stage Swarm Planning Framework for Efficient Multi-Drone Waypoint Traversal," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 827-834, doi: 10.1109/IROS60139.2025.11247604.

Link https://ieeexplore.ieee.org/document/11247604

A UKF-based Loose Coupling Framework for Odometry Fusion

Keywords

SLAM, multi-sensor fusion, UKF, sensor failure

Abstract

Odometry fusion is crucial for mobile robots with various types of sensors. However, traditional odometry fusion approaches often suffer from high complexity and limited robustness, particularly in complex environments with few features. To address these challenges, a loose coupling framework based on the UKF is introduced for odometry fusion. By integrating multiple odometry sources using the UKF, the framework enhances both accuracy and robustness in localization and mapping. The experimental results in indoor and outdoor scenes verified the effectiveness of the proposed method, which can not only improve the accuracy of localization and mapping but also can handle the situation if partial sensors are not functioning.

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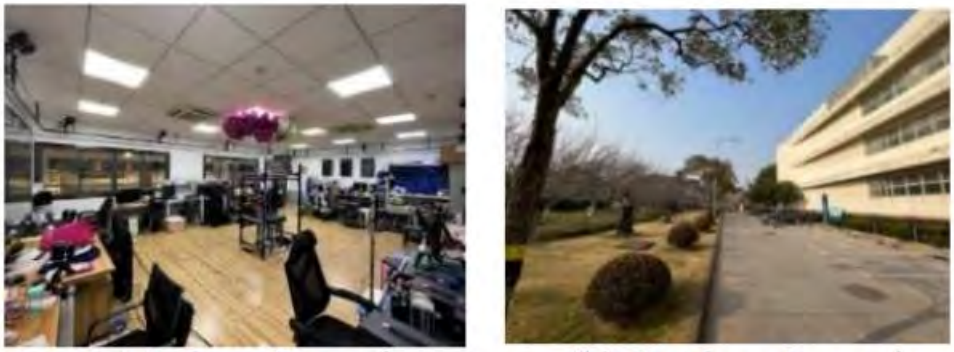

(a) Indoor Scenario (b) Outdoor Scenario

How NOKOV Contributes to the Research

The experiments are conducted in two different scenarios. The first scenario is the indoor lab as shown in Fig. 2(a), and the ground truth in the scene is captured with the high-precision motion capture system NOKOV MARS4H. The second scenario is the outdoor scene at Shanghai University as illustrated in Fig. 2(b). The associated ground truth trajectory is obtained based on the Hi-Target differential GPS.

Citation Xie Y, Zhang J, Qian W, et al. A UKF-based Loose Coupling Framework for Odometry Fusion[C]//2023 2nd International Conference on Automation, Robotics and Computer Engineering (ICARCE). IEEE, 2023: 1-6.

Link https://ieeexplore.ieee.org/abstract/document/10492592

Active Collision-Based Navigation for Wheeled Robots

Keywords

Computer vision; Three-dimensional displays; Codes; Pipelines; Data acquisition; Benchmark testing; Motion capture; Dataset; Hand-object Interaction; Motion Synthesis; Action Recognition; Motion Capture

Abstract

Humans commonly work with multiple objects in daily life and can intuitively transfer manipulation skills to novel objects by understanding object functional regularities. However, existing technical approaches for analyzing and synthesizing hand-object manipulation are mostly limited to handling a single hand and object due to the lack of data support. To address this, we construct TACO, an extensive bimanual hand-object-interaction dataset span-ning a large variety of tool-action-object compositions for daily human activities. TACO contains 2.5K motion se-quences paired with third-person and egocentric views, pre-cise hand-object 3D meshes, and action labels. To rapidly expand the data scale, we present a fully automatic data acquisition pipeline combining multi-view sensing with an optical motion capture system. With the vast research fields provided by TACO, we benchmark three generalizable hand-object-interaction tasks: compositional action recognition, generalizable hand-object motion forecasting, and cooperative grasp synthesis. Extensive experiments reveal new insights, challenges, and opportunities for advancing the studies of generalizable hand-object motion analysis and synthesis. Our data and code are available at https://taco2024.github.io.

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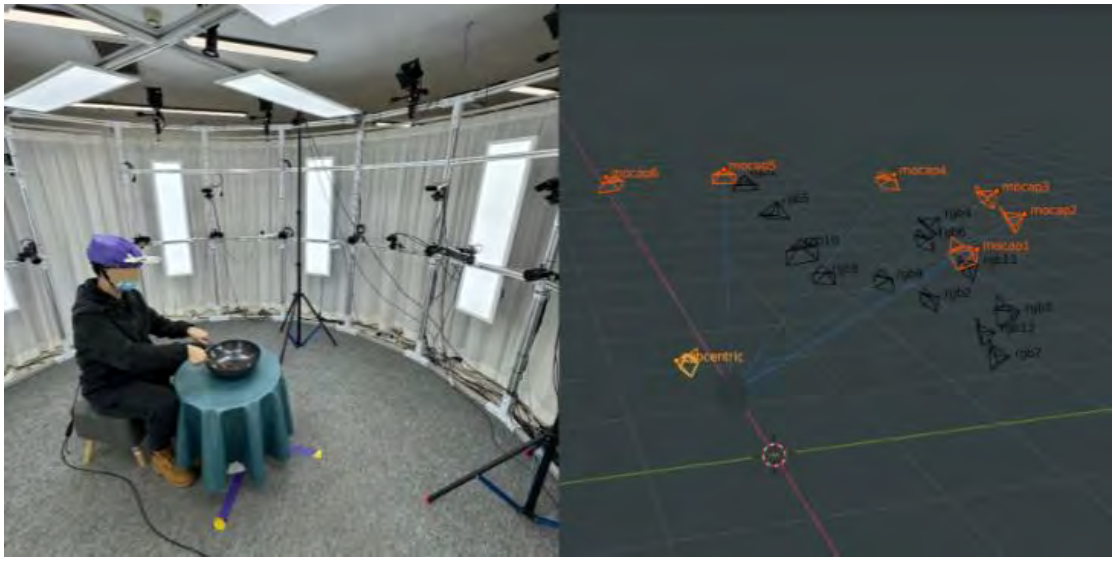

How NOKOV Contributes to the Research

Our data capturing system incorporates 12 synchronized industrial FLIR cameras and a NOKOV optical motion capture suite with 6 infrared Mars4H cameras. NOKOV optical motion capture suite is utilized to capture the object motion.

Citation J. Li, J. Ji, Q. Wang, H. Yu, Y. Pan and F. Gao, "Active Collision-Based Navigation for Wheeled Robots," 2024 IEEE International Conference on Robotics and Automation (ICRA), Yokohama, Japan, 2024, pp. 10932-10938, doi: 10.1109/ICRA57147.2024.10610726.

Link https://ieeexplore.ieee.org/document/10610726

Adaptive Decision-Making in Attack-Defense Games With Bayesian Inference of Rationality Level

Keywords

Attack-defense (AD) game, Bayesian learning, level-k theory, receding horizon optimization

Abstract

This article investigates two-player attack-defense (AD) games involving players with bounded rationality, where the defender aims to intercept the attacker, while the attacker aims to invade the protected area and avoid interception. We first set path planning optimization problems in a receding horizon fashion for each player and formulate the AD game. Then, using the level- $\boldsymbol{k}$ model of behavioral game theory, we specify the decision mechanisms for players with bounded rationality. We propose an adaptive path planning strategy, coupled with the Bayesian learning method, for the defender to counter the attacker with an unknown reasoning level of the decision mechanism. The Bayesian inference algorithm, which combines current observation information and historical receding horizon prediction trajectories to form the belief on the attacker's reasoning level, allows the defender to generate an adaptive interception trajectory with the multimodel strategy. Finally, both numerical simulations and experiments confirm the effectiveness of the proposed algorithm.

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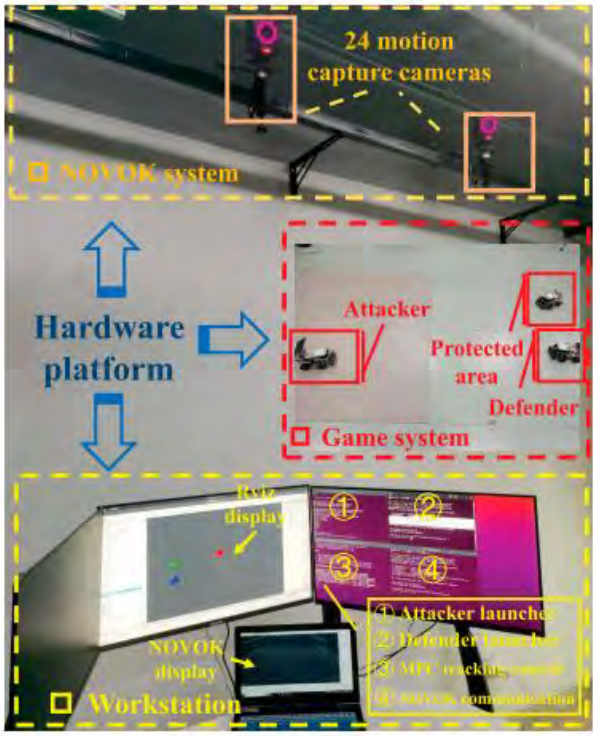

Fig. 6. Hardware platform.

How NOKOV Contributes to the Research

The hardware platform was built with three main modules,the game system, the NOVOK system and the workstation. In the game system, three autonomous ground vehicles (AGVs)represent the attacker, the defender, and the protected area. Inthe NOKOV system, 24 motion capture cameras are used tocapture the motion states of all the vehicles.

Citation Fang H, Yi P. Adaptive Decision-Making in Attack-Defense Games With Bayesian Inference of Rationality Level[J]. IEEE Transactions on Industrial Electronics, 2024, 71(12): 16558-16567.

Link https://www.x-mol.com/paper/1796237727832272896

Adaptive game-theoretic decision-making with driving style recognition for autonomous vehicles in uninterrupted traffic flows at intersections

Keywords

Autonomous vehicles, Decision making, Game theory, Uninterrupted traffic flows, Driving style

Abstract

The absence of standardized conflict resolution mechanisms presents critical challenges for autonomous vehicles operating in uninterrupted traffic flows, particularly when managing time-sensitive interactions with heterogeneous road users. Existing approaches either adopt overly conservative policies by oversimplifying multi-agent interactions or neglect the critical influence of heterogeneous driving styles. This paper proposes a game-theoretic decision-making framework for autonomous vehicles in uninterrupted traffic flow scenarios, specifically designed to address the intertwined challenges of multi-objective optimization and driving style adaptation. A hierarchical game-theoretic architecture integrates kinematic state evolution, feasibility constraints, and interactive behavior modeling to rigorously model multi-vehicle interactions under dynamic mixed traffic conditions. A novel online identification mechanism estimates driving styles through real-time interaction pattern analysis, while a machine learning-driven adaptive framework generates parametric policies through offline random forest training coupled with context-aware online policy adjustments. Comprehensive simulations validate the framework's effectiveness in both single and multiple intersection scenarios, demonstrating enhanced interaction adaptability (more than 10% efficiency improvements) compared to conventional non-adaptive methods. Experimental results demonstrate the model's capability to efficiently handle heterogeneous driving behaviors and dynamically refine negotiation strategies, providing a systematic, human-like vehicle decision-making solution for mixed traffic environments.

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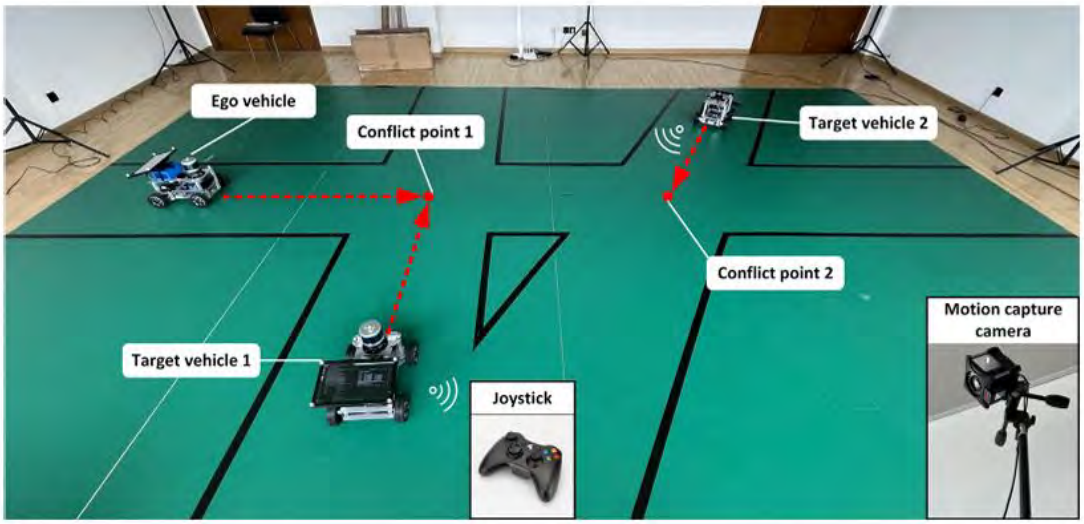

Fig. 5. Experiment scenario.

How NOKOV Contributes to the Research

Our methodology undergoes rigorous physical validation through ROS-enabled SmartCars in a hardware-in-the-loop testbed. As illus-trated in Fig. 5, the experiment platform replicates uninterrupted uncontrolled intersections through a small-size physical model with millimeter-accuracy localization. A distributed perception system em-ploying eight industrial-grade motion capture cameras (NOKOV motion capture system) streams real-time vehicle states to autonomous agents via ROS topics, achieving sub-centimeter positional precision.

Citation Cao, Yuxiao, Yinuo Jiang, and Xiangrui Zeng. "Adaptive game-theoretic decision-making with driving style recognition for autonomous vehicles in uninterrupted traffic flows at intersections." Robotics and Autonomous Systems (2025): 105180.

Link https://www.sciencedirect.com/science/article/abs/pii/S0921889025002775

Adaptive Pure Pursuit: A Real-Time Path Planner Using Tracking Controllers to Plan Safe and Kinematically Feasible Paths

Keywords

Path planning, autonomous driving, cluttered environment, pure pursuit control, adaptive pure pursuit (APP)

Abstract

Path planning is an essential function in an intelligent vehicle, especially when driving in scenarios cluttered by large-scale static obstacles. Traditional path planners often struggle to find a balance among speed, accuracy, and optimality in their solutions. In this article, we introduce an Adaptive Pure Pursuit (APP) planner, which is designed to be fast and near-optimal for autonomous driving in cluttered environments. The APP planner generates feasible paths through a simulated closed-loop tracking control process of a virtual vehicle. If a derived path encounters obstacles, an adaptive refinement step is taken to locally reduce these collisions. Unlike search-based planners that suffer from the "curse of dimensionality" and optimization-based methods that often run slowly, the APP planner operates extremely fast. The high speed stems from the fact that both the virtual controller simulation and the refinement step involve computations with zero degrees of freedom. The proposed APP planner outperforms the prevalent optimization-based and search-based path planners, as shown by comparative simulations.

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Fig. 8. Field test scenario layout and device setups.

How NOKOV Contributes to the Research

A car-like robot of dimensions 0.211m × 0.191m was utilized as the ego vehicle. Six infrared sensors from the NOKOV Motion Capture System were deployed for precise vehicle and obstacle localization.

Citation Li B, Wang Y, Ma S, et al. Adaptive pure pursuit: A real-time path planner using tracking controllers to plan safe and kinematically feasible paths[J]. IEEE Transactions on Intelligent Vehicles, 2023.

Link https://ieeexplore.ieee.org/abstract/document/10185581

Adaptive Risk-Aware Multi-Target Tracking and Monitoring With Network Reconfiguration

Keywords

Adaptive control, heterogeneous multi-robot systems, multi-target tracking, resilience

Abstract

We consider a scenario in which a group of robots tracks a group of targets in an open space. In particular, the robots are heterogeneous, and the targets are adversarial, capable of attacking the robots and severing the links between the robots and their corresponding sensors. Additionally, each robot is required to estimate the state of the targets individually on the basis of the communication graph. We propose a framework that adaptively balances accuracy and safety while automatically repairing the communication graph. Our framework follows a two-stage strategy: In the first stage, we assess the entire team to determine if repair is necessary. If necessary, by quantifying the team's observability using the trace of the Grammian matrix, we propose a computationally efficient repair strategy. In the second stage, safety and accuracy are quantified, with the sensing margin serving as the dynamic weight to guide robot coordination. To validate the effectiveness of our work, we simulated a monitoring and tracking task and compared our network reconfiguration strategy with greedy and One-Hop-Grammian-based methods. The simulation results demonstrate the effectiveness and efficiency of our approach.

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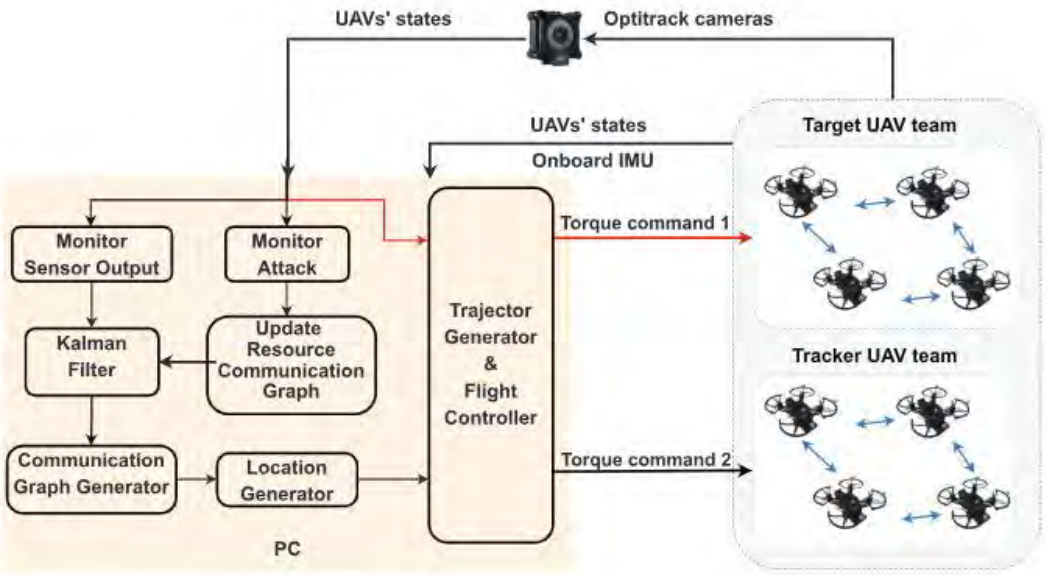

Fig. 6. Data flow of the experiment.

How NOKOV Contributes to the Research

To validate the proposed algorithms, we conduct the exper-iment on the corresponding platform with four quadrotorstracking the other four quadrotors. The quadrotors are theDroneyee 'Feisi' X150, and the Optitrack system is the NOKOV. A photograph of the experiment is shown in Fig. 5.

Citation Cui Y, Wang J, Zheng C, et al. Adaptive Risk-Aware Multi-Target Tracking and Monitoring With Network Reconfiguration[J]. IEEE Transactions on Circuits and Systems I: Regular Papers, 2025.

Link https://ieeexplore.ieee.org/document/11029637

Adaptive Shape Formation Against Swarm-Scale Variants in Robot Swarms

Keywords

Adaptive shape formation, variable swarm scale, density feedback, mean-shift algorithm, multi-robot systems

Abstract

Shape formation of robot swarms is quite challenging when the robot number varies, as the number often needs to match the number of goal locations in the shape. For this challenge, state-of-the-art methods characterize the shape as a continuous region and distribute robots in the region. However, such methods can only handle a small swarm-scale variant due to the fixed shape size. In this letter, we propose a distributed adaptive shape formation method with variable shape size. The core idea is that each robot can dynamically adjust the shape size according to variants of local density, induced by variants of the robot number. Furthermore, this individual adjustment by each robot can be propagated through peer-to-peer communications. In particular, this strategy is integrated into our previous work, which employs the mean-shift algorithm to achieve the shape formation of large-scale robot swarms. In addition, we also adapt the mean-shift algorithm for redesigning all the negotiation and control components in the previous work such that a concise and unified alternative for shape formation can be provided via the mean-shift algorithm. Finally, simulation and experiment results demonstrate that the proposed method can achieve the desired shape with the robot number decreasing or increasing.

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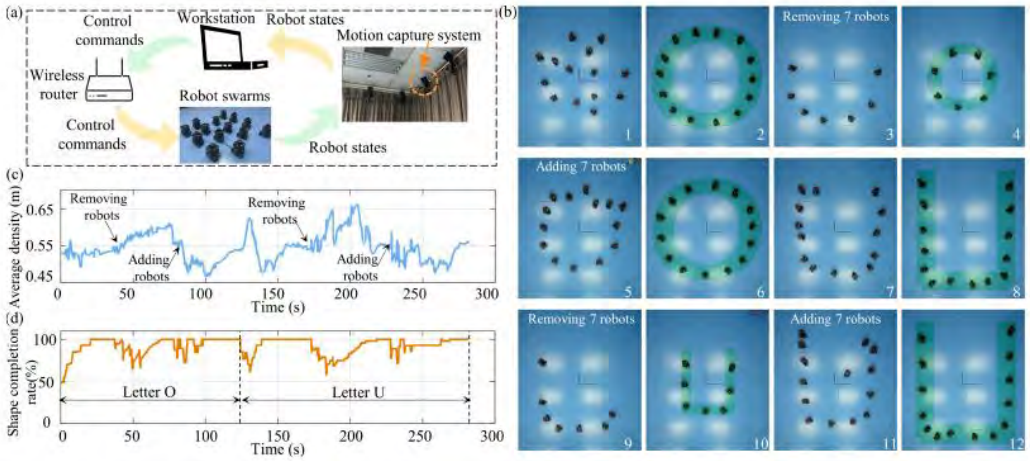

Fig. 5. Experiment setup and results. (a) Experiment setup. (b) Snapshots in this experiment, the snapshots 1–6, and 6–12 show the adaptive formation process of letter "O", and "U", where 2–4, and 4–6 show the removal and addition of robots when forming "O"; 8–10, and 10–12 show the removal and addition of robots when forming "U". (c) Average density of robots in swarm over time in this experiment. (d) The shape completion rate over time in this experiment.

How NOKOV Contributes to the Research

Real-time states can be obtained via a Nokov Mocap system (motion capture system) while control commands are delivered to robots via the wireless router.

Citation Li X, Zhou R, Sun G. Adaptive shape formation against swarm-scale variants in robot swarms[J]. IEEE Robotics and Automation Letters, 2024, 9(8): 6776-6783.

Link https://ieeexplore.ieee.org/document/10556623

Aggressive and robust low-level control and trajectory tracking for quadrotors with deep reinforcement learning

Keywords

Reinforcement learning, Low-level control, Trajectory tracking, Quadrotor, Robustness

Abstract

Executing accurate trajectory tracking tasks using a high-performance low-level controller is crucial for quadrotors to be applied in various scenarios, especially those involving uncertain disturbances. However, due to the uncertainties in disturbed environments, developing effective low-level controllers with traditional model-based control schemes is challenging. This paper presents an aggressive and robust reinforcement learning (RL)-based low-level control policy for quadrotors. The policy maps the observed quadrotor state directly to motor thrust commands, without requiring the quadrotor dynamics. Additionally, a trajectory generation pipeline is developed to improve the accuracy of trajectory tracking tasks based on differential flatness. With the learned low-level control policy, extensive simulations and real-world experiments are implemented to validate the performance of the policy. The results indicate that our RL-based low-level control policy outperforms traditional proportional–integral–derivative (PID) control methods and related learning-based policies in terms of accuracy and robustness, particularly in environments with uncertain disturbances. Furthermore, the proposed RL-based control policy exhibits an aggressive response in trajectory tracking, even when the speed of the desired trajectory is increased to 6 m/s. Moreover, the learned policy demonstrates strong vibration suppression capabilities and enables the quadrotor to recover to a hovering state from random initial conditions with shorter response time.

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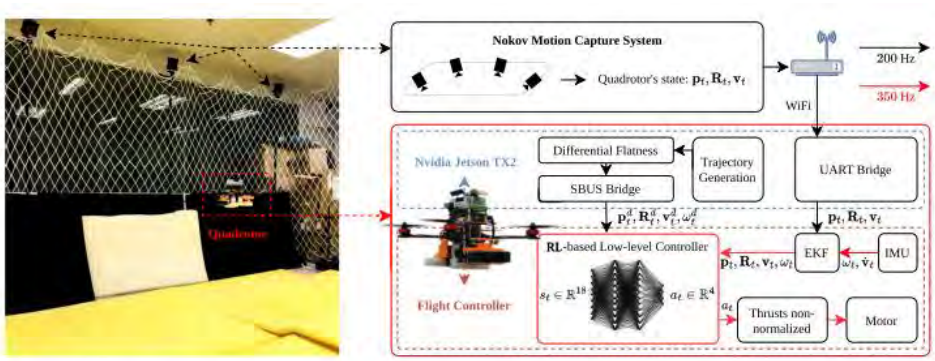

Fig. 15 Software framework of the custom quadrotor platform used for the low-level control and trajectory tracking tasks in real-world experiments

How NOKOV Contributes to the Research

The original observedquadrotor state is obtained from the Nokov motion capturesystem at a frequency of 200 Hz. Then, an extended Kal-man filter (EKF) \[45] is used to improve the accuracy andoutput frequency of the observed state by fusing the orig-inal state with the measured information from onboardinertial measurement unit (IMU).

Citation Chen S, Li Y, Lou Y, et al. Aggressive and robust low-level control and trajectory tracking for quadrotors with deep reinforcement learning[J]. Neural Computing and Applications, 2025, 37(3): 1223-1240.

Link https://link.springer.com/article/10.1007/s00521-024-10675-4

Agile Flights Through a Moving Narrow Gap for Quadrotors Using Adaptive Curriculum Learning

Keywords

Quadrotor, reinforcement learning, agile flight, gap-traversing

Abstract

Fast and agile flying through a gap is challenging for a quadrotor if the gap is narrow, tilted, and moving. Due to the strict time-variant position and attitude constraints, collision-free traversal trajectories under the under-actuated quadrotor dynamics are sparse and difficult to solve. To achieve this challenging task in the real world, we propose a Gap-Traversing Adaptive Curriculum Learning (GTACL) approach, which consists of adaptive curriculum reinforcement learning (ACRL) and online thrust updating (OTU). First, ACRL is introduced to improve sample efficiency, and the policy training is accelerated by designing a curriculum adapted to the agent's capability. Second, OTU is proposed to map the acceleration commands to low-level throttle signals by estimating the thrust model during flight, which reduces the intermediate control variables and helps sim2real transfer. We use the prioritized experience replay mechanism that considers both policy update contribution and data acquisition time to adapt to the changing tasks. GTACL is trained entirely in simulation and can be transferred to other quadrotors with different dynamics. Furthermore, we achieve zero-shot transfer to the real-world quadrotor without fine-tuning. The average success rates of 98% and 87.8% in simulation and real-world experiments for different task conditions demonstrate the robustness of the proposed approach. Comparative results with traditional and related learning-based approaches show the advantages of GTACL in terms of learning efficiency, control performance, and generalization.

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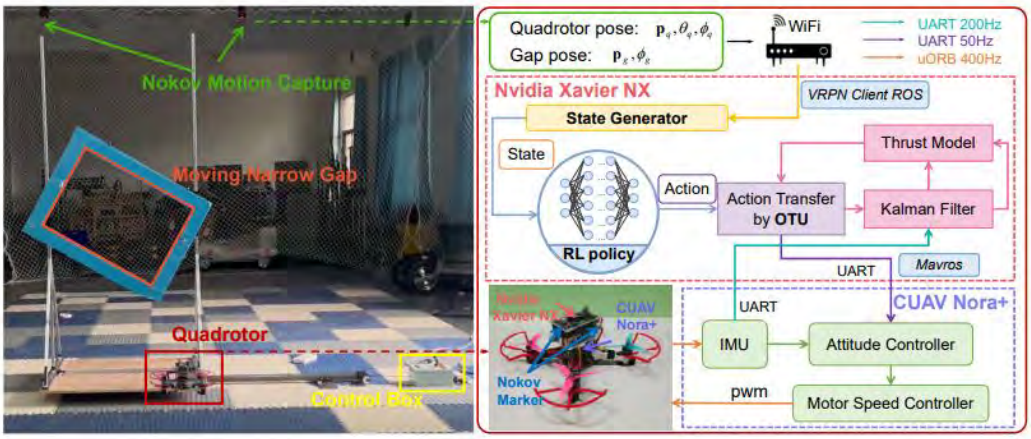

Fig. 12. The real-world experiment system. The quadrotor platform comprises the quadrotor frame, a CUAV Nora+ flight controller, and a Xavier NX onboard computer. All experiments are conducted indoors, with the Nokov motion capture system providing poses of the quadrotor and the gap. The variable speed of the gap is achieved by the control box.

How NOKOV Contributes to the Research

The real-world experiment system. The quadrotor platform comprises the quadrotor frame, a CUAV Nora+ flight controller, and a Xavier NX onboard computer. All experiments are conducted indoors, with the Nokov motion capture system providing poses of the quadrotor and the gap. The variable speedof the gap is achieved by the control box.

Citation Wang M, Jia S, Niu Y, et al. Agile Flights Through a Moving Narrow Gap for Quadrotors Using Adaptive Curriculum Learning[J]. IEEE Transactions on Intelligent Vehicles, 2024.

Link https://ieeexplore.ieee.org/document/10505852

Air Shepherd: Trajectory Prediction-Based Target Localization and Circumnavigation in Cluttered Environments

Keywords

Cluttered environments, distributed control, tracking and circumnavigation, trajectory prediction, autonomous aerial vehicles (AAVs)

Abstract

This paper proposes a trajectory prediction-based target localization and circumnavigation pattern for cluttered three-dimensional environments, which is more realistic and suitable for more complex environments than traditional patterns. The main work of the paper consists of two parts: tracking based on trajectory prediction and circumnavigation based on broadcast information. On the one hand, the tracking Autonomous Aerial vehicle (AAV) obtains target trajectory prediction based on the B-spline curve, and then achieves target localization and tracking through front-end search and back-end optimization. On the other hand, without communicating with each other, a distributed control strategy is presented so that the multiple circumnavigation AAVs can achieve target circumnavigation and reciprocal avoidance by only observing the status of adjacent AAVs. In the simulation, obstacle avoidance vehicles moving freely at different speeds are selected as targets in two scenarios and the simulation results are given to verify the effectiveness of the proposed approach. Furthermore, a hardware-in-the-loop experiment and a overall system validation experiment are designed to verify the feasibility of the algorithm. Note to Practitioners—Practical tracking scenarios often involve numerous obstacles, and it is difficult to determine the location of the target being tracked and surrounded. Many existing methods assume that the trajectory or position of the tracked target is already known, but in reality, this assumption is difficult to fulfill due to the agility of the target and the complexity of the environment. Compared to existing work, this paper proposes an 'air shepherd' mechanism, in which a tracking AAV plays the role of a 'sheepdog', and based on trajectory prediction, the target can still be tracked even when it is out of sight. The circumnavigation AAVs play the role of the 'sheep', achieving pursuit and encirclement without requiring communication between each other while ensuring reciprocal avoidance.

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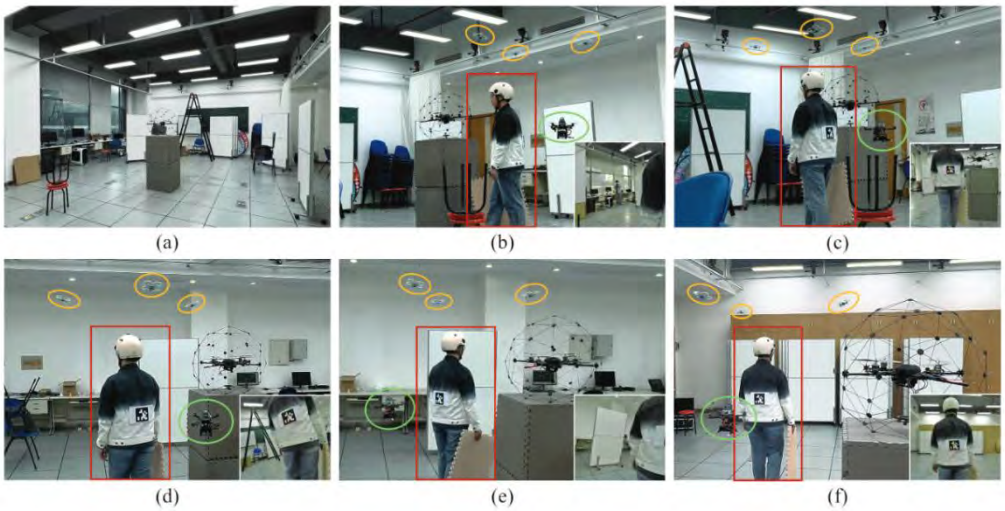

Fig. 21. Screenshots of the overall system validation experimental results. (a) Overall system validation experimental environment. (b)-(f) Screenshots of the overall system validation experimental results. The red rectangle represents the target, the green ellipse represents the tracking AAV, and the yellow ellipses represent the circumnavigation AAVs. In each subplot, the bottom right corner shows the image captured by the monocular camera at the corresponding time. In (c), (d) and (f), the target is visible, while in (b) and (e), the target is out of view.

How NOKOV Contributes to the Research

During the experimental process, we use the motion capturesystem (NOKOV) to record the target's true position. Thetracking AAV performs environmental perception, online prediction, and real-time planning based on the identified target'sposition, and transmits both the target position and predictionresults to the host workstation. The host workstation calculatesthe control inputs and sends them to each circumnavigation AAV in real time via the local network.

Citation Rao K, Yan H, Ren H, et al. Air Shepherd: Trajectory Prediction-based Target Localization and Circumnavigation in Cluttered Environments[J]. IEEE Transactions on Automation Science and Engineering, 2025.

Link https://ieeexplore.ieee.org/document/10948410

Air-Ground Cooperative Path Planning for Doorstep Pickup Considering Multiple Uncertainty

Keywords

Air-ground heterogeneous robots, chance constraints, first-mile pickup, path planning, time windows

Abstract

Air-ground heterogeneous robots collaboration can efficiently handle first-mile pickups and reduce reverse logistics costs. When an uncrewed ground vehicle (UGV) and an uncrewed aerial vehicle (UAV) collaborate for doorstep pickups, the UAV handles customer pickups while the UGV acts as a mobile warehouse, providing replenishment and transportation services. This setup enables long-distance, large-scale, and flexible logistics. However, real-world collaborative pickups face uncertainties in pickup times and parcel weights, complicating path planning. To address the challenge, this article aims to minimize the total travel distance for UAV and UGV and formulates a path planning model with time windows under uncertainty and designs an adaptive genetic large neighborhood search (AGLNS) algorithm for solution. Through numerical simulations and comparative analysis, the method's scalability and adaptivity to uncertainty has been validated extensively. Real-world experiments confirm the method's effectiveness and feasibility. These findings offer both theoretical guidance and practical insights for air-ground robot path planning, contributing to improved logistics efficiency and cost reduction.

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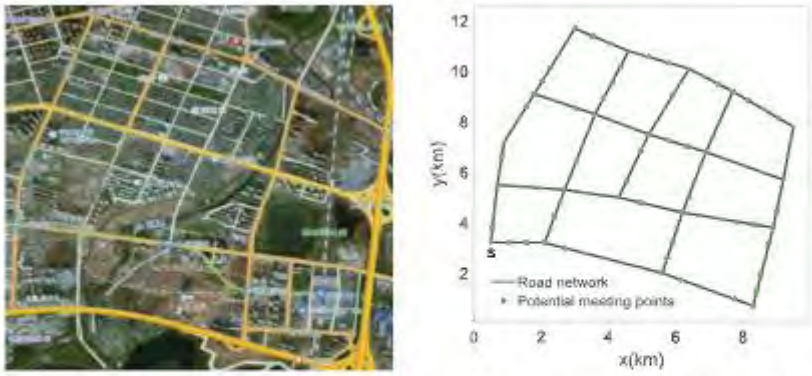

(a) Road network (b) Discretized topological graph

Fig. 1. The road network and discretized topological graph of a certain urban area in Wuhan

How NOKOV Contributes to the Research

The real-world experiment utilizedthe NOKOV Motion Capture System, which consists of 12cameras positioned around the perimeter to capture a 6m×4mindoor space. The UAV and UGV were equipped with motioncapture markers

Citation Tian L, Chen Y, Wu H, et al. Air-Ground Cooperative Path Planning for Doorstep Pickup Considering Multiple Uncertainty[J]. IEEE Sensors Journal, 2025.

Link https://ieeexplore.ieee.org/document/11006352

Air-M: A Visual Reality Many-agent Reinforcement Learning Platform for Large-Scale Aerial Unmanned System

Abstract

Reinforcement learning for swarms of flying robots is a challenging task that requires a large number of data samples. Moreover, the problem of sim-to-real transfer has long been a challenge in robotics algorithm deployment. To address these issues, we propose Air-M, a platform that facilitates large-scale drone swarm learning in a distributed docker container environment and deployment in a virtual reality setting. Air-M trains the policy network using physics engines and creates replicas of agents in docker containers, which helps amortize the computational cost. In addition, Air-M establishes an intermediate link between the simulation and the real world, allowing real drones to interact with virtual objects via virtual sensors. This enables the policy network to be trained using virtual agents and seamlessly transferred to real drones. Air-Mis highly scalable, accommodating hundreds of agents with dynamic models and virtual sensors. We evaluate the effectiveness of our approach by conducting experiments in three representative virtual scenarios with an increasing number of agents. Our results demonstrate that our method outperforms the state-of- the-art in terms of training efficiency and transferability, making it a promising platform for swarm robotics applications.

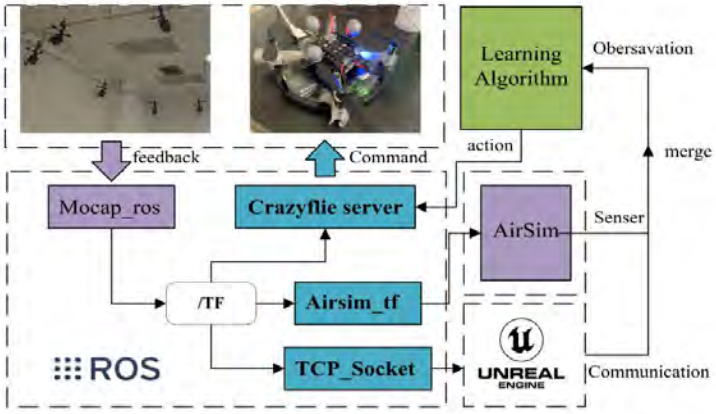

Fig. 4: Physical Experiment Testbed, it contains the external positioning system, the UAV control system, and the UAV ontology

How NOKOV Contributes to the Research

As shown in Figure. 4, we used the NOKOV Motion Capture System and modified the ROS driver of the crazyflie to enable the Mocap positioning.

Citation J. Lou, W. Wu, S. Liao and R. Shi, "Air-M: A Visual Reality Many-Agent Reinforcement Learning Platform for Large-Scale Aerial Unmanned System," 2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Detroit, MI, USA, 2023, pp. 5598-5605, doi: 10.1109/IROS55552.2023.10341405.

Link https://ieeexplore.ieee.org/search/searchresult.jsp?newsearch=true&queryText=Air-M:%20A%20Visual%20Reality%20Many-agent%20Reinforcement%20Learning%20Platform%20%20for%20Large-Scale%20Aerial%20Unmanned%20System

An adaptive reinforcement learning approach with trait-awareness for heterogeneous multi-robot cooperative pursuit

Keywords

Multi-robot pursuit, Reinforcement learning, Composite robotics team, Mutual information

Abstract

Multi-robot cooperative pursuit is a critical task that has been extensively studied in domains such as military, security and rescue operations. However, most of the existing methods focus on homogeneous assumptions with limited research exploring heterogeneous teams. Moreover, they fail to generalize learned policies to new team compositions. In this paper, Heterogeneous team compositions with diverse capabilities are considered and we propose an Adaptive Trait-Aware framework (HATA) to address these challenges. First, we propose an adaptive trait encoding module to capture team heterogeneity and produce expressive representations for heterogeneous robots. Second, a trait-aware behavior module is designed to generate different collaborative pursuit actions based on the distinct traits of heterogeneous robots. Consequently, composite teams can leverage the strengths of different traits to achieve efficient coordination. In addition, we introduce a novel training paradigm with a regularization term to enhance robustness to unseen heterogeneous configurations. Our method facilitates comprehensive planning of coalition cooperation without the need for domain knowledge or expert experience. Finally, we conducted experiments in a pursuit scenario with obstacles, and the final results show that our method achieves a 95.1% success rate while using only 35.2% of the maximum number of steps to complete the task. Additionally, we deploy the proposed method on a physical multi-drone platform to validate its real-world applicability.

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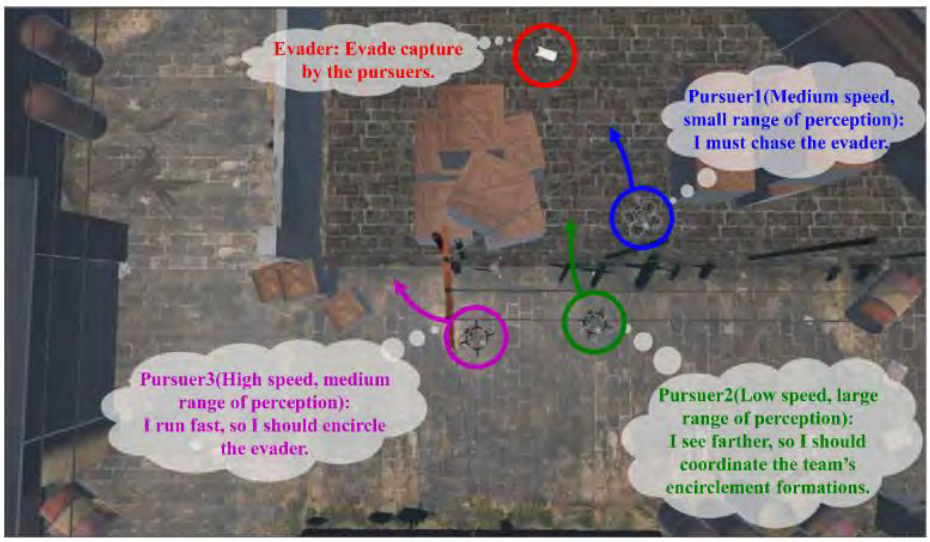

Fig. 1. Illustration of cooperative pursuit in heterogeneous multi-robot systems. In this task, all pursuers coordinate to approach and encircle the evader, effectively restricting its movement.

How NOKOV Contributes to the Research

5.5.Physical demonstration
In this section, we perform physical experiments to assess the feasi-bility of HATA. The experimental platform is shown in Fig. 11. Giventhe small form factor of drones, we utilize the Crazyflie 2.l droneswarm operating in an experimental environment of 5 m x 5 m toevaluate the performance of our model. The NOKOV motion capture system is adopted to provide millimeter-level position measurement sof drones by detecting a set of infrared markers mounted on top ofthe drones. Additionally, we utilize a workstation as a communication node in the whole system. The workstation connects with the NOKOV system to collect the position information through a switch, whichis then transmitted to each drone via the Crazyradio PA. Therefore, although each drone is not equipped with an object detection sensorit can indirectly detect other drones and obstacles. Based on

Citation Zhang H, Jia Y, Song Y, et al. An adaptive reinforcement learning approach with trait-awareness for heterogeneous multi-robot cooperative pursuit[J]. Engineering Applications of Artificial Intelligence, 2025, 160: 112037.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001576856400001

An Efficient Trajectory Planner for Car-like Robots on Uneven Terrain

Keywords

Tracking, Heuristic algorithms, Dynamics, Stochastic processes, Approximation algorithms, Tires, Planning

Abstract

Autonomous navigation of ground robots on uneven terrain is being considered in more and more tasks. However, uneven terrain will bring two problems to motion planning: how to assess the traversability of the terrain and how to cope with the dynamics model of the robot associated with the terrain. The trajectories generated by existing methods are often too conservative or cannot be tracked well by the controller since the second problem is not well solved. In this paper, we propose terrain pose mapping to describe the impact of terrain on the robot. With this mapping, we can obtain the SE(3) state of the robot on uneven terrain for a given state in SE(2). Then, based on it, we present a trajectory optimization framework for car-like robots on uneven terrain that can consider both of the above problems. The trajectories generated by our method conform to the dynamics model of the system without being overly conservative and yet able to be tracked well by the controller. We perform simulations and real-world experiments to validate the efficiency and trajectory quality of our algorithm.

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How NOKOV Contributes to the Research

In order to validate the performance of our method in realworld applications, we deploy it on a car-like robot, as shown in Fig. 3. All computations are performed by an onboard computer NVIDIA Jetson Nano. We utilize NOKOV Motion Capture System2 for localization. Furthermore, a MPC controller with position feedback is fitted to the robot for trajectory tracking.

Citation L. Xu et al., "An Efficient Trajectory Planner for Car-Like Robots on Uneven Terrain," 2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Detroit, MI, USA, 2023, pp. 2853-2860, doi: 10.1109/IROS55552.2023.10341558.

Link https://ieeexplore.ieee.org/document/10341558

Anticipation promotes the velocity alignment in collective motion

Keywords

Anticipation, Collective behavior, Velocity alignment, Swarm robots

Abstract

Anticipation is a fundamental capacity found in many living organisms, particularly in humans. In this study, we investigate the influence of anticipation on collective behavior based on a self-propelled model that relies on solely attractive interaction forces. Focal particles employ anticipation to predict the future positions of neighboring particles, foreseeing their locations τ time steps ahead by utilizing linear extrapolation based on adjacent time step positions. The results demonstrate that our model can attain velocity alignment from random initial states. Theoretical derivations further reveal that as both τ and the interaction amplitude among particles increase, the translation velocity of the swarm accelerates. Notably, under certain parameters, noise above a certain value can drive swarm from misaligned to the velocity alignment state. These insights have been validated through both particle simulations and experiments employing swarm robots. Our work reveals the significant role of anticipation in collective behavior and provides a novel approach for achieving velocity alignment in swarm.

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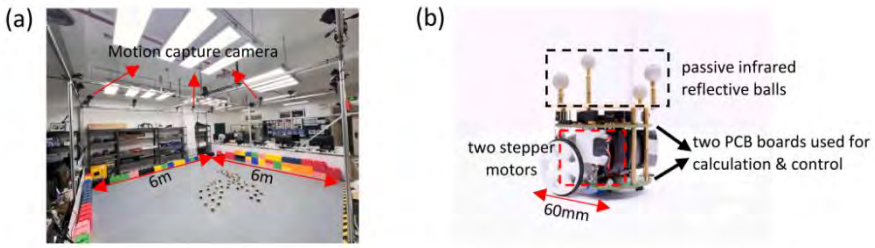

Fig. 8. SwarmBang: a swarm robots experiment system. (a) The experimental ground. (b) The SwarmBang robots.

How NOKOV Contributes to the Research

We use the motion capture camera manufactured byNOKOVto capture the position/velocity of AGVs.
Fig. 8(a) shows the 6m\6 m square experiment ground of SwarmBang system. Above the experimental ground, there are 16 motion capture cameras manufactured byNOKOV.

Citation Zhou Y, Wang T, Wang T, et al. Anticipation promotes the velocity alignment in collective motion[J]. Physica A: Statistical Mechanics and its Applications, 2024, 637: 129601.

Link https://www.sciencedirect.com/science/article/abs/pii/S0378437124001092

Antiswing Control Strategy for Quadrotor Transporting a Cable-Suspended Payload: A Two-Stage ADRC Approach

Keywords

Active disturbance rejection control (ADRC), antiswing control, quadrotor slung-load system (QSLS), step-extended state observer

Abstract

In order to deal with the control problem of a quadrotor with a cable-suspended payload, a novel antiswing control strategy based on a two-stage active disturbance rejection control (ADRC) is proposed in this article. The process of lifting the payload from the ground is considered, and the whole control can be divided into three stages accordingly, which is different from most existing works. The ADRC-based control algorithm is applied at each stage to attenuate the effect of unknown external disturbances, and a step-extended state observer is introduced specially to ensure tracking performance during the transient stage. Furthermore, the concept of virtual position is introduced to deal with the swing motion of the suspended payload generated during the quadrotor's trajectory tracking. Based on the virtual position, a novel quadrotor position controller is designed, which can improve the antiswing performance and disturbance rejection capabilities simultaneously. Numerical simulations and experiments have validated the effectiveness of the proposed method at the end of the article.

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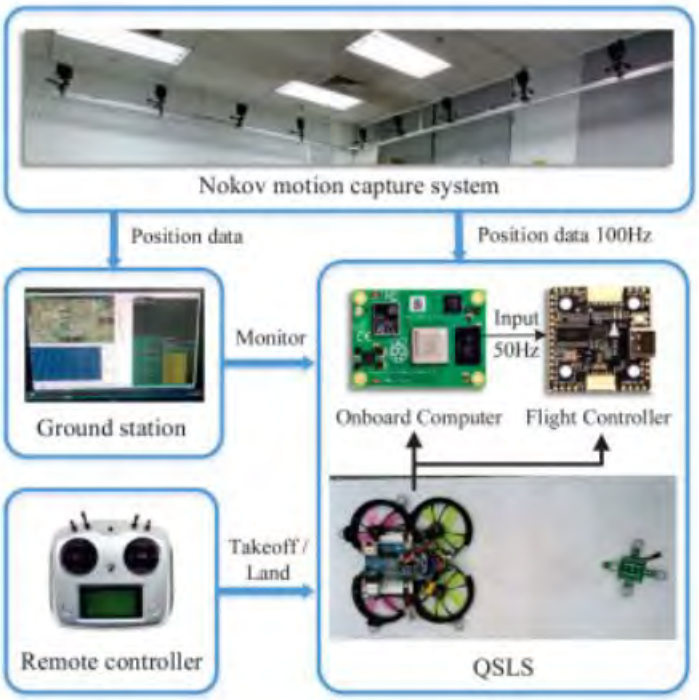

Fig. 10. Architecture of the antiswing control experimental platform.

How NOKOV Contributes to the Research

The antiswing control experimentalplatform consists of a Nokov motion capture system, a groundstation, a quadrotor controlled by a flight control board andonboard computer, and a payload. The position information ofthe quadrotor and payload is obtained by the motion capturesystem and transmitted to the quadrotor and ground station at afrequency of 100 Hz. The onboard computer of the quadrotorruns the control algorithm in ROS and calculates the controlsignal based on the received position information and attitude information obtained from its own sensors.

Citation Zhao K, Zhang J, Shu P, et al. Antiswing Control Strategy for Quadrotor Transporting a Cable-Suspended Payload: A Two-Stage ADRC Approach[J]. IEEE/ASME Transactions on Mechatronics, 2024.

Link https://ieeexplore.ieee.org/document/10701524

Asynchronous multithreading reinforcement learning with attention-based significance measurement for collision-free robot navigation

Keywords

Robotic vehicle, Reinforcement learning, Collision-free navigation, Significance measurement, Local attention

Abstract

Collision avoidance is one crucial technique to achieve safe and efficient robotic vehicle navigation in unknown environments. However, moving obstacles with unpredictability in dynamic scenarios, usually increase the difficulty and complexity in collision avoidance of robotic vehicles. To enhance the stability of collision avoidance and boost its adaptability to uncertain dynamic scenes, a new attention-based significance measurement actor-critic (ASMAC) architecture is proposed. It is an end-to-end robot navigation model that uses imperfect local observation to directly plan precise collision-free motion commands. Firstly, a significance-measured rollout replaybuffer (SMRR) is presented to categorize the experiences into different pools. It can prevent any overfitting or bias that may result from repeatedly sampling experience of a certain type during policy learning. Then, we enhance the traditional actor-critic network by integrating a multi-head local attention module to extract the local information at entity level. This way, the collision avoidance system can focus on key environmental features to compute more lightweight and respond more swiftly to dynamic changes in environment. Besides, a multi-step lookahead prediction (MLP) reward function is designed in the ASMAC-based reinforcement learning (RL) framework to prevent the generation of unnatural, intrusive, and short-sighted motion decisions. Finally, the asynchronous multithreading (AM) mechanism and proximal policy optimization (PPO) algorithm are extended to ASMAC model to offload the expensive online computation to an offline training process, enhancing the exploration efficiency in navigation policy learning of robotic vehicles. Extensive simulation and real-world physical experiments show that our method can generate time-efficient and collision-free guide paths in complex dynamic scenes, to successfully dodge collisions while moving towards the goal.

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Fig. 1. AGV navigation with limited sensing in complex dynamic environments.

How NOKOV Contributes to the Research

To further test the generalization capabilities of our navigationmodel in real world, we use a self-developed differential-driving robotprototype to demonstrate our model, as shown in Fig. 13. The sensorsare a Rplidar A2 Lidar (used for obstacle detection), a Kinect V2camera (used for moving object detection Sun et al., 2023), and a NOKOV motion capture system (used for indoor global localization).These sensor kits provide the observations for AGV. Then, AGV executesaction commands output from our navigation system that consists of asoftware framework (ROS Kinetic in Ubuntu16.04) and an industrialcomputer (Intel Core i7-9800X CPU 8-GB RAM). Although there is noperfect state knowledge, as was available in simulation, the AGV canavoid collisions using only on-board sensing.

Citation Sun C, Wang J, Wu X, et al. Asynchronous multithreading reinforcement learning with attention-based significance measurement for collision-free robot navigation[J]. Engineering Applications of Artificial Intelligence, 2026, 167: 113779.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001665318400001

Attention-based Value Classification Reinforcement Learning for Collision-free Robot Navigation

Keywords

Robotic vehicle, collision-free navigation, reinforcement learning, value classification, local attention

Abstract

Collision avoidance is a crucial technique to achieve safe and efficient robotic vehicle navigation in unknown environments. However, moving obstacles with unpredictability in dynamic scenarios, usually increase the difficulty and complexity in collision avoidance of robotic vehicles. To enhance the stability of collision avoidance and boost its adaptability to uncertain dynamic scenes, a new attention-based value classification actor-critic (AVCAC) architecture is proposed. It is an end-to-end robot navigation model that utilizes imperfect local observation to directly plan accurate collision-free motion commands. First, we design a value-classified rollout replaybuffer to categorize the experiences into different pools. It can prevent any overfitting or bias that may result from repeatedly sampling experiences of a certain type during policy learning. Then, we improve the conventional actor-critic network with a multi-head local attention module to extract the local observations at entity-level. This way, the collision avoidance system can focus on key environmental features to operate more efficiently and respond more swiftly to dynamic changes in the environment. Moreover, a lookahead multi-step prediction (LMP) reward setting is devised in the AVCAC-based reinforcement learning (RL) framework to facilitate more informed and forward-looking decision-making. Finally, the policy entropy (PE) and policy delay (PD) are extended to AVCAC model to enhance policy exploration and make policy more robust. Extensive experimental results reveal that our method can generate time-efficient and collision-free guide paths to dodge collisions under complex dynamic environments.

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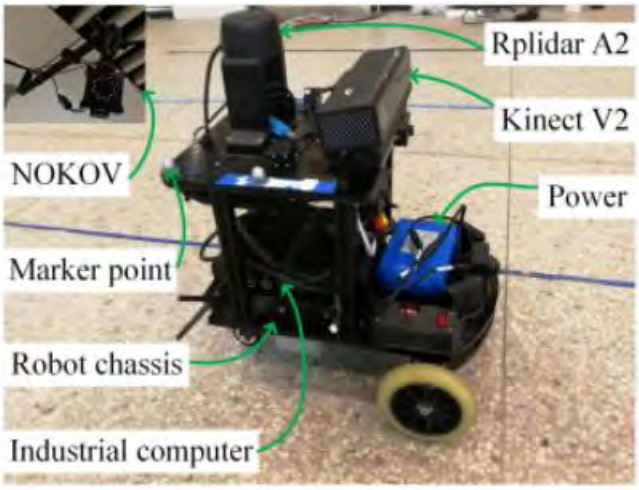

Fig. 12. Robot prototype for collision-free navigation experiments.

How NOKOV Contributes to the Research

The sensors are a Rplidar A2 Lidar (used for obstacle detection), a Kinect V2 camera (used for moving object detection), and a NOKOV motion capture system (used for indoor globallocalization). These sensor kits provide the observations for AGV.

Citation Sun C, Wu X, Wang Y, et al. Attention-based value classification reinforcement learning for collision-free robot navigation[J]. IEEE Transactions on Intelligent Vehicles, 2024.

Link https://ieeexplore.ieee.org/document/10504956

Automated Discovery of Efficient Behavior Strategies for Distributed Shape Formation of Swarm Robots by Genetic Programming

Keywords

Swarm robots, genetic programming, shape formation

Abstract

The distributed shape formation (DSF) of swarm robots is to form a specific shape, where each robot autonomously selects and moves to one target position in the desired shape. In this paper, we design some basic behaviors to construct behavior strategies, in which the swap selector and the obstacle avoidance planner are designed to guide robots in mitigating the negative effects of deadlock and collision during the DSF task. We propose a framework based on multi-agent simulation and genetic programming (GP) to automatically discover efficient behavior strategies followed by each robot to achieve DSF efficiently. The framework is distinguished by a centralized optimization of behavior strategies followed by each robot, along with strategy-driven decentralized decision-making and execution processes. In centralized optimization, to find behavior strategies with better generalization regarding shape types, a shape generator is designed to generate diverse training instances for comprehensively evaluating each behavior strategy in multi-agent simulation. Then, GP is used to evolve behavior strategies. In decentralized decision-making and execution, each robot can be guided by the same behavior strategy to form the shape. In terms of DSF completion time, the behavior strategies discovered by GP outperform the state-of-the-art distributed algorithm significantly across all test instances. These strategies can be well applied to different instances beyond the training instances. Through the statistical analysis, we also identify some crucial behaviors for realizing DSF. Note to Practitioners—This paper was motivated by a problem of distributed shape formation (DSF) for swarm robots but it also applies to other complex systems such as distributed task allocation and motion planning of swarm. Existing distributed algorithms (manually designed heuristics) can solve the DSF problem quickly but rely too much on human experience and cannot sufficiently mine the associations between behaviors and states of robots. Evolutionary algorithms are inspired by natural processes such as reproduction, mutation, and natural selection, enabling them to automatically evolve heuristic rules. The evolved heuristic rules possess the ability to adapt to

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dynamic environments in real time. To the best of our knowledge, while evolutionary algorithms have not been extensively explored in DSF, notable advancements have been achieved in complex systems such as swarm robots and industrial production. Considering that robots need to respond to dynamic states of robots in real time and the tree-structure representation facilitates the construction of associations between the states and behaviors of robots, we employ GP to search the space of heuristic rules instead of directly searching the solution space about the position-robot assignment and motion planning. Computational experiment results show that the DSF completion time by the evolved behavior strategies is remarkably reduced as compared to that of the manually designed the state-of-the-art heuristics in most test instances. In the future, we plan to explore the possibility of enabling robots to dynamically generate shapes that can adapt to complex environments.

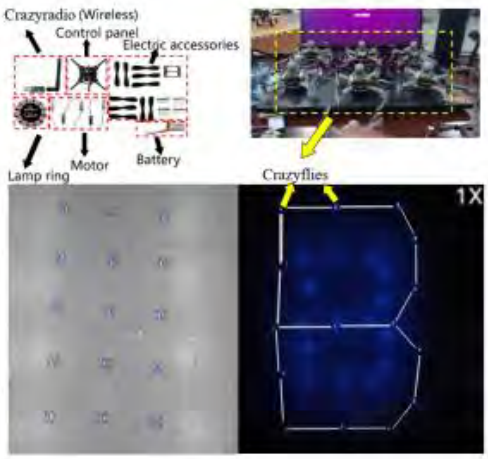

Fig. 17. 15 robots form the shape B.

How NOKOV Contributes to the Research

To verify the correctness and efficiency of the generatedbehavior strategy, a custom-made swarm of 15 Crazyflies3.0 is shown in Fig. 17. We use a NOKOV motion trackingsystem for localization. A computer workstation uses separateprocesses for each robot to manage and receive the positionof its own. Commands are sent to Crazyflies 3.0 directly overtheir custom radio.

Citation Qu Y, Xin B, Wang Q, et al. Automated Discovery of Efficient Behavior Strategies for Distributed Shape Formation of Swarm Robots by Genetic Programming[J]. IEEE Transactions on Automation Science and Engineering, 2023, 21(4): 7599-7615.

Link https://ieeexplore.ieee.org/document/10375949

Automatic Generation of Aerobatic Flight in Complex Environments via Diffusion Models

Abstract

Performing striking aerobatic flight in complex environments demands manual designs of key maneuvers in advance, which is intricate and time-consuming as the horizon of the trajectory performed becomes long. This paper presents a novel framework that leverages diffusion models to automate and scale up aerobatic trajectory generation. Our key innovation is the decomposition of complex maneuvers into aerobatic primitives, which are short frame sequences that act as building blocks, featuring critical aerobatic behaviors for tractable trajectory synthesis. The model learns aerobatic primitives using historical trajectory observations as dynamic priors to ensure motion continuity, with additional conditional inputs (target waypoints and optional action constraints) integrated to enable user-editable trajectory generation. During model inference, classifier guidance is incorporated with batch sampling to achieve obstacle avoidance. Additionally, the generated outcomes are refined through post-processing with spatial-temporal trajectory optimization to ensure dynamical feasibility. Extensive simulations and real-world experiments have validated the key component designs of our method, demonstrating its feasibility for deploying on real drones to achieve long-horizon aerobatic flight.

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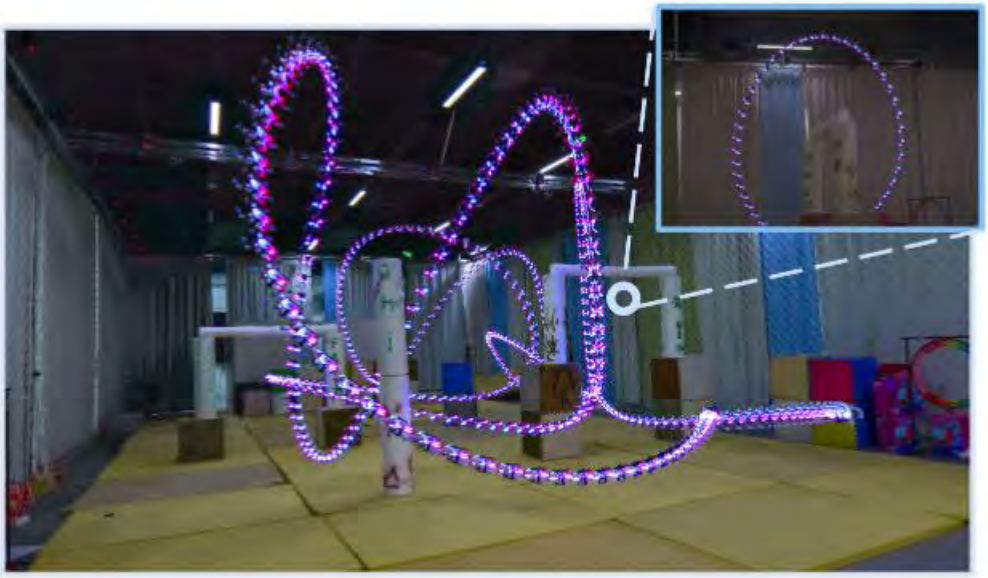

Fig. 8: Snapshot of a quadrotor executing aerobatic flight trajectories with five distinct maneuvers generated by the proposed method in real-world.

How NOKOV Contributes to the Research

To verify the real-world applicability of the proposed method, the aerobatic trajectories containing five aerobatic maneuvers are generated in a narrow and cluttered indoor space with the size of 12×6×4 m312×6×4m3, where a drone executes these trajectories under the NOKOV Motion Capture System11. The real-world performance is demonstrated in Fig. 8, with the numerical analysis provided in Fig. 9. As Fig. 9 indicates, the post-processing constrains the thrust and angular velocity to remain within feasible values, ensuring that the low-level controllers can accurately track the control signals.

Citation Y. Zhong, A. Zhao, T. Wu, T. Zhang and F. Gao, "Automatic Generation of Aerobatic Flight in Complex Environments via Diffusion Models," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 21235-21242, doi: 10.1109/IROS60139.2025.11246023.

Link https://ieeexplore.ieee.org/document/11246023

Autonomous Navigation of Quadrotors in Dynamic Complex Environments

Keywords

Aerial robotics, Motion planning, Velocity obstacle.

Abstract

This article introduces a novel framework utilizing velocity obstacles to enhance the autonomous navigation of quadrotors in dynamic complex environments. In this framework, quadrotors rely on onboard sensors to perceive the surrounding environment and construct an occupancy grid map for environmental representation. The density-based spatial clustering of applications with noise (DBSCAN) algorithm is employed to extract the positions and velocities of dynamic obstacles within the environment. Based on these results, we propose a velocity obstacle-based gradient field, called gradient velocity obstacle (GVO), for generating collision-free velocities ensuring safety.Compared with existing methods,GVOpreserves the original feasible set while ensuring computational efficiency. Moreover, it exhibits excellent fault tolerance to environmental perception noise. Additionally, we design motion primitives based on B-spline parameterization. By optimizing within position and velocity state spaces, collision-free trajectories are dynamically constructed in real-time. Extensive simulations and experiments validate our framework's effectiveness, showcasing significant improvements in navigation efficiency and safety. The experimental section of the entire work can be found at the following link: https://www.youtube.com/watch?v=TOEeoFO4OxY .

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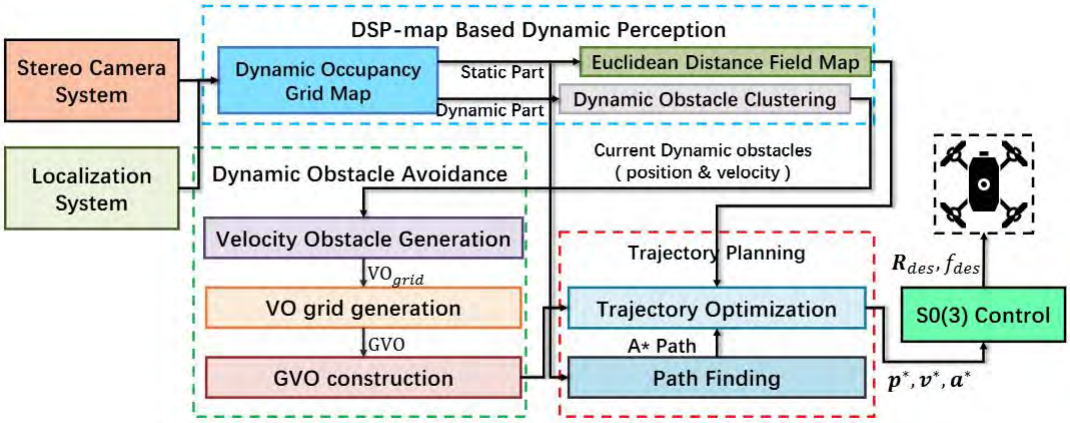

Fig. 1: A block diagram illustrating the full pipeline of the proposed planning framework.

How NOKOV Contributes to the Research

To validate the performance of the proposed approach in real-world scenarios, we conduct extensive field experiments in complex indoor environments. The quadrotor platform we used is shown in Fig. 9. We perform localization based on our previous work [3], use DSP-Map [33]+DBSCAN to update the occupancy grid map and use the NOKOV motion capture system as the ground truth.

Citation R. Li and B. Xin, "Autonomous Navigation of Quadrotors in Dynamic Complex Environments," in IEEE Transactions on Industrial Electronics, doi: 10.1109/TIE.2024.3433585.

Link https://ieeexplore.ieee.org/abstract/document/10649014

Autonomous Positioning for Mobile Vehicles Based on Visual-Inertial Fusion in Challenging Dark Roadway Scenes

Keywords

hybrid features detection, inertial navigation system, underground autonomous positioning, visual-inertial fusion

Abstract

Accurate positioning for autonomous driven underground mining vehicles (UMVs) and coal mine robots (CMRs) is indeed one of the cores in the intelligentization of coal mining. Completely different from positioning on the ground and in parking scenes, there will be great difficulties in realizing the accurate active positioning for UMVs shuttled in dark and narrow roadways. We propose an effective visual and inertial fusion positioning method for autonomous CMRs and roadheaders in challenging roadway scenarios based on the odometer - aided inertial navigation system and visual pose estimation system. Velocity information of the odometer is adapted to restrain the error accumulation of inertial positioning based on a Kalman filter. The hybrid visual feature detection algorithm is put forward to improve the accuracy and robustness of visual observation information in a dark environment. Autonomous experiments for CMRs and roadheaders are separately performed in the narrow roadway and dark passageway to demonstrate the applicability of our localization method. The proposed approach outperforms the subsystems and existing methods in accuracy and has outstanding stability.

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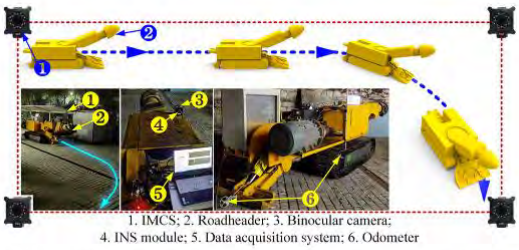

FIGURE 10 | Experiment II: roadheader prototype positioning in dark passageway. [Color figure can be viewed at wileyonlinelibrary.com]

How NOKOV Contributes to the Research

The experimental systems for CMRs and roadheaders mainly consist of INS module, Binocular camera, odometer, data acquisition and processing system, and infrared motion capturesystem (IMCS).
The relative position of all sensors and the true trajectory of CMR and roadheader are measured through several infrared markers by IMCS.

Citation Cui Y, Pu J, Hu N, et al. Autonomous Positioning for Mobile Vehicles Based on Visual -Inertial Fusion in Challenging Dark Roadway Scenes[J]. Journal of Field Robotics, 2025, 42(4): 1333-1343.

Link https://onlinelibrary.wiley.com/doi/10.1002/rob.22454

Barycentric Coordinate-Based Distributed Localization for Mobile Sensor Networks Under Denial-of-Service Attacks

Keywords

Denial-of-service (DoS) attacks, distributed localization, mobile sensor networks

Abstract

Localization is a key technology to ensure the effective operation of wireless sensor networks in different environments. Due to the prevalence of cyber-attacks in real-world application scenarios, ensuring the accuracy of localization under denial-of-service (DoS) attacks is a growing concern. Existing research focuses on distributed localization of static sensor networks under DoS attacks. This article aims to extend the study of distributed localization in mobile sensor networks subject to DoS attacks. Under DoS attacks, communication between sensor nodes can become intermittent, resulting in the time-varying characteristic for communication networks among all sensor nodes, which poses a challenge for successful localization. To overcome this challenge, this article proposes a distributed iterative localization algorithm using relative barycentric coordinates and distance measurements. Based on a hybrid approach composed of graph composition and sub-stochastic matrix, a comprehensive analysis of the convergence, rate and complexity of the localization algorithm is presented. At last, the theoretical results are verified by experimental examples.

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Fig. 9. Experimental platform based on robots and NOKOV system.

How NOKOV Contributes to the Research

The indoor localization is provided by the NOKOV optical 3-D motion capture system, which consistsof 24 Mars 4H camera lenses that can track the target marker points from different angles to complete the location capture.

Citation Shi L, Shi H, Ma Z, et al. Barycentric coordinate-based distributed localization for mobile sensor networks under denial-of-service attacks[J]. IEEE Transactions on Industrial Informatics, 2024, 20(5): 8019-8030.

Link https://ieeexplore.ieee.org/abstract/document/10462621

Body orientation change of neighbors leads to scale-free correlation in collective motion

Keywords

Intelligent nursing wheelchairs, Mecanum wheels, Mecanum wheel mobility chassis, Suspension mechanism

Abstract

Intelligent nursing wheelchairs significantly enhance mobility and independence for elderly individuals with disabilities. However, traditional designs often suffer from large turning radii that restrict their functionality in confined spaces. Addressing this critical challenge, this study introduces an innovative design utilizing a Mecanum wheel chassis that allows for omnidirectional movement, significantly improving maneuverability and stability. Our design incorporates independently controlled Mecanum wheels, overcoming traditional constraints and enhancing user autonomy. To address issues such as wheel spacing variations and hub center tilting, which can lead to slipping and inaccurate motion control, we developed a novel suspension system that stabilizes the chassis, minimizes slipping risks, and boosts motion control accuracy. Experimental validations, including shock absorption and positioning tests, demonstrate that our suspension system markedly enhances the wheelchair's control performance and stability, thereby providing users with enhanced precision and potentially improving their quality of life.

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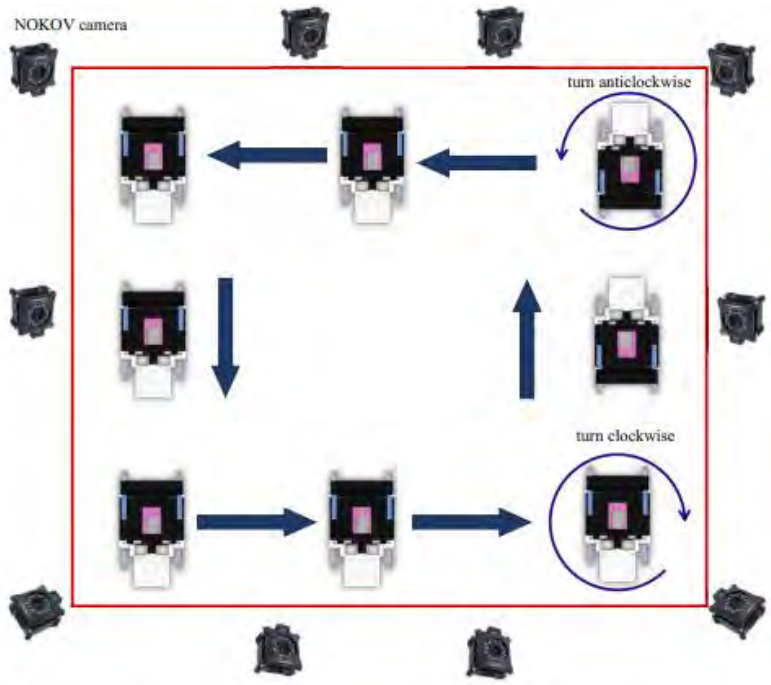

Fig. 11. Test the wheelchair movement trajectory with the NOKOV camera.

How NOKOV Contributes to the Research

The workflow of our validation system begins with the measure-ment of each SwarmBang robot's position and heading via the NOKOV motion capture system processed on the server computer (see Sup-plementary Note 6 and Supplementary Fig. 17 for detailed informa-tion). Next, the server computer simulates the local vision-basedsensing of the robots through the pinhole camera model (see Sup-plementary Note 6 for detailed information). Then, the server com-puter determines the desired heading $\theta d$for each robot based on the swarm model and the simulated local perception.

Citation Zheng Z, Tao Y, Xiang Y, et al. Body orientation change of neighbors leads to scale-free correlation in collective motion[J]. Nature Communications, 2024, 15(1): 8968.

Link https://link.springer.com/article/10.1038/s41467-024-53361-8

Cascaded Active Disturbance Rejection Control for Quadrotor Trajectory Tracking

Keywords

Quadrotor, trajectory tracking, ADRC, disturbance rejection

Abstract

In this paper, a cascaded control structure for quadrotor trajectory tracking problem is investigated based on the active disturbance rejection control (ADRC). For the position controller, a third order extended state observer (ESO) is developed to estimate the disturbances, and an ADRC controller is established. Then for the attitude stabilization, a dual-loop control scheme is applied since the angular velocity can be measured. An ESO is introduced to the inner-loop angular velocity controller to enhance the robustness. Simulations indicate that the proposed method can achieve a quick and smooth tracking, while enhance the robustness. Moreover, the tracking performance and the capacity of disturbance rejection is verified via two set of experiments.

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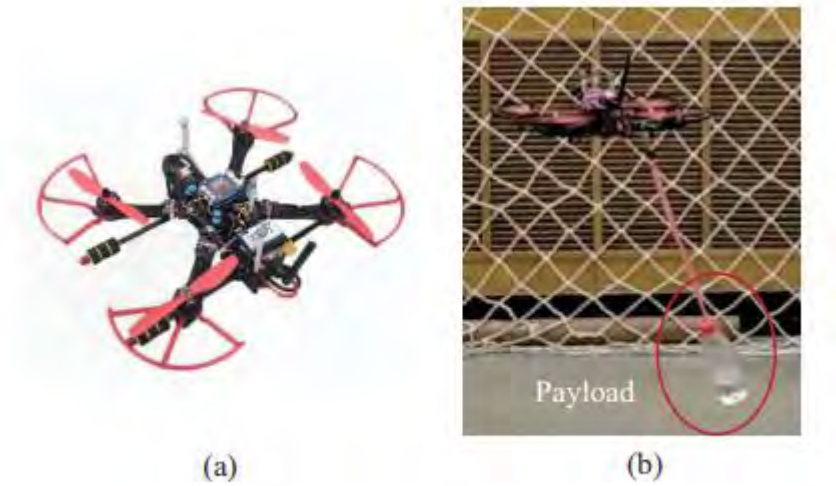

Fig. 6. Experimental platform.

How NOKOV Contributes to the Research

The experimental platformin this paper is built based onQAV-250 quadrotor frame and ANO-Pioneer flight control unit. The attitude ismeasured by on-board inertialmeasurement unit (IMU) ICM20602, and the position is obtained by Nokovmotion capture system. The actuator consists of EMAXMT2204 DCmotor and 5045 propeller. The experimentalplatformis shown in Fig. 6(a).

Citation Han F, Hao C, Deng Z. Cascaded active disturbance rejection control for quadrotor trajectory tracking[C]//2019 Chinese Automation Congress (CAC). IEEE, 2019: 5385-5390.

Link https://ieeexplore.ieee.org/abstract/document/8997411

Collaborative Control of UAV Swarms for Target Capture Based on Intelligent Control Theory

Keywords

multi-UAV, target capture, differential game, closed circular pipeline, real-time dynamics, pursuit and evasion

Abstract

Real-time dynamic capture of a single moving target is one of the most crucial and representative tasks in UAV capture problems. This paper proposes a multi-UAV real-time dynamic capture strategy based on a differential game model to address this challenge. In this paper, the dynamic capture problem is divided into two parts: pursuit and capture. First, in the pursuit–evasion problem based on differential games, the capture UAVs and the target UAV are treated as adversarial parties engaged in a game. The current pursuit–evasion state is modeled and analyzed according to varying environmental information, allowing the capture UAVs to quickly track the target UAV. The Nash equilibrium solution in the differential game is optimal for both parties in the pursuit–evasion process. Then, a collaborative multi-UAV closed circular pipeline control method is proposed to ensure an even distribution of capture UAVs around the target, preventing excessive clustering and thereby significantly improving capture efficiency. Finally, simulations and real-flight experiments are conducted on the RflySim platform in typical scenarios to analyze the computational process and verify the effectiveness of the proposed method. Results indicate that this approach effectively provides a solution for multi-UAV dynamic capture and achieves desirable capture outcomes.

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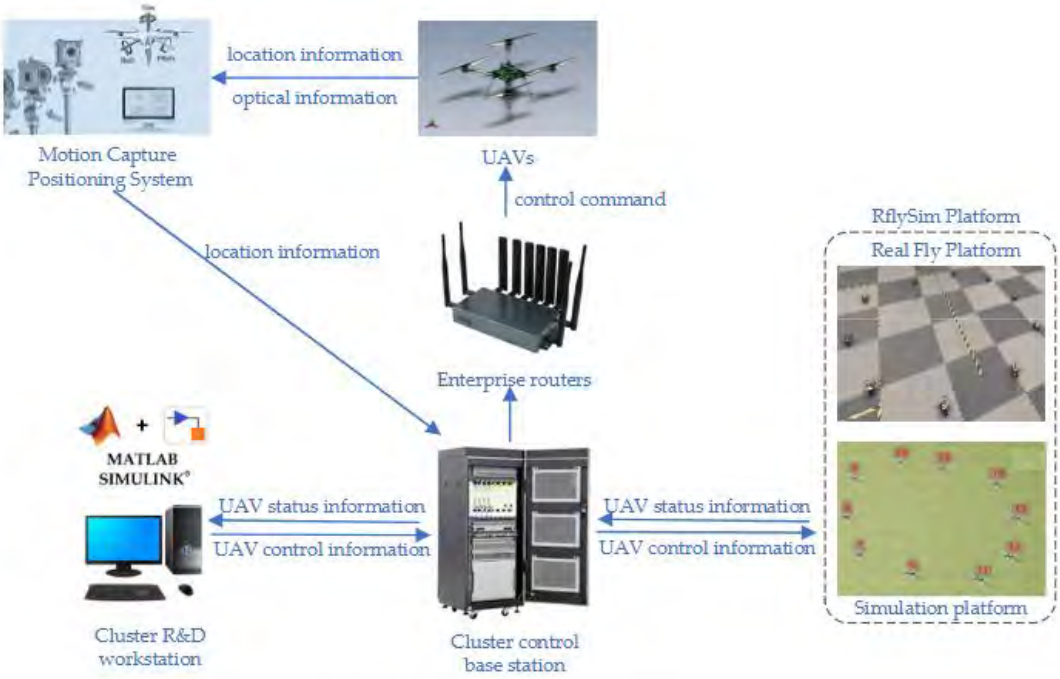

Figure 6. Physical schematic connection diagram.

How NOKOV Contributes to the Research

Simulink ' s automatic code generation feature allowed for convenient and automaticcontroller deployment to the hardware, facilitating HIL simulation and real flight testing toachieve Sim2Real. Figure 6 shows the connection mode of the hardware device.

Citation Chi Y, Dong Y, Zhang L, et al. Collaborative Control of UAV Swarms for Target Capture Based on Intelligent Control Theory[J]. Mathematics, 2025, 13(3): 413.

Link https://www.mdpi.com/2227-7390/13/3/413

Communication-aided multi-UAV collision detection and avoidance based on two-stage curriculum reinforcement learning

Keywords

Collision detection and avoidance, End-to-end, Multi-UAV, Two-stage, Curriculum reinforcement learning

Abstract

Currently, multi-UAV collision detection and avoidance is facing many challenges, such as navigating in cluttered environments with dynamic obstacles while equipped with low-cost perception devices having a limited field of view (FOV). To this end, we propose a communication-aided collision detection and avoidance method based on curriculum reinforcement learning (CRL). This method integrates perception and communication data to improve environmental understanding, allowing UAVs to handle potential collisions that may go unnoticed. Furthermore, given the challenges in policy learning caused by the substantial differences in scale between perception and communication data, we employ a two-stage training approach, which performs training with the network expanded from part to whole. In the first stage, we train a partial policy network in an obstacle-free environment for inter-UAV collision avoidance. In the second stage, the full network is trained in a complex environment with obstacles, enabling both inter-UAV collision avoidance and obstacle avoidance. Experiments with PX4 software-in-the-loop (SITL) simulations and real flights demonstrate that our method outperforms state-of-the-art baselines in terms of reliability of collision avoidance, including the DRL-based method and NH-ORCA (Non-Holonomic Optimal Reciprocal Collision Avoidance). Besides, the proposed method achieves zero-shot transfer from simulation to real-world environments that were never experienced during training.

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(a) Initial state (t=0 s) (b) Intermediate state (t=6.77 s) (c) End state (t=19.2 s)

Fig. 9. The snapshots of the real flight driven by CACDA-CRL. We use four colors to identify different UAVs. Boxes block some drones due to the shooting angle. The sub-figures in the upper right corner indicate their current positions.

How NOKOV Contributes to the Research

4.4. Evaluations in a real-world cluttered environment
A multi-UAV system, as shown in Fig.8, is constructed toevaluate the performance of the proposed method on real-world platforms. The UAV frame is the D]I F450, powered by T-MotorAir Gear 450 motors, with the Pixhawk 4 as the autopilot. Theonboard computer is the Nvidia Xavier NX, and the LiDAR sensoris the Hokuyo UST-05LX, which offers precise distance measure.ment capabilities up to five meters. The flight area is about20 x 20 x 9 m in size and is equipped with 72 Nokov cameras.The Nokov motion capture system' is used to track the positionsof the UAVs, which are broadcast using UAV networks.

Citation Wang G, Wang X, Miao Z, et al. Communication-aided multi-UAV collision detection and avoidance based on two-stage curriculum reinforcement learning[J]. Biomimetic Intelligence and Robotics, 2025: 100253.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001609699900001

Concurrent-Learning Based Relative Localization in Shape Formation of Robot Swarms

Keywords

Relative localization, shape formation, concurrent-learning, robot swarms

Abstract

In this article, we address the shape formation problem for massive robot swarms in environments where external localization systems are unavailable. Achieving this task effectively with solely onboard measurements is still scarcely explored and faces some practical challenges. To solve this challenging problem, we propose the following novel results. Firstly, to estimate the relative positions among neighboring robots, a concurrent-learning based estimator is proposed. It relaxes the persistent excitation condition required in the classical ones such as the least-square estimator. Secondly, we introduce a finite-time agreement protocol to determine the shape location. This is achieved by estimating the relative position between each robot and a randomly assigned seed robot. The initial position of the seed one marks the shape location. Thirdly, based on the theoretical results of the relative localization, a novel behavior-based control strategy is devised. This strategy not only enables the adaptive shape formation of large groups of robots but also enhances the observability of inter-robot relative localization. Numerical simulation results are provided to verify the performance of our proposed strategy compared to the state-of-the-art ones. Additionally, outdoor experiments on real robots further demonstrate the practical effectiveness and robustness of our methods. Note to Practitioners—Shape formation has a broad potential for large groups of robots to execute certain tasks, such as object transport, forest firefighting, and entertainment shows. However, most of the existing approaches rely on external localization infrastructures, rendering them impractical in environments where such systems are not available. To address this issue, this article proposes an integrated strategy that can achieve shape formation for large groups of robots by using local distance and displacement measurements. This strategy consists of three main components. Firstly, a relative localization estimator is introduced to estimate the relative positions among neighboring robots. Secondly, a protocol for reaching a consensus on the desired shape's position is proposed. Thirdly, a behavior-based controller is developed to achieve massive shape formation and enhance the observability of relative localization. More details of the proposed algorithms and swarm robotic systems are provided in this artic.

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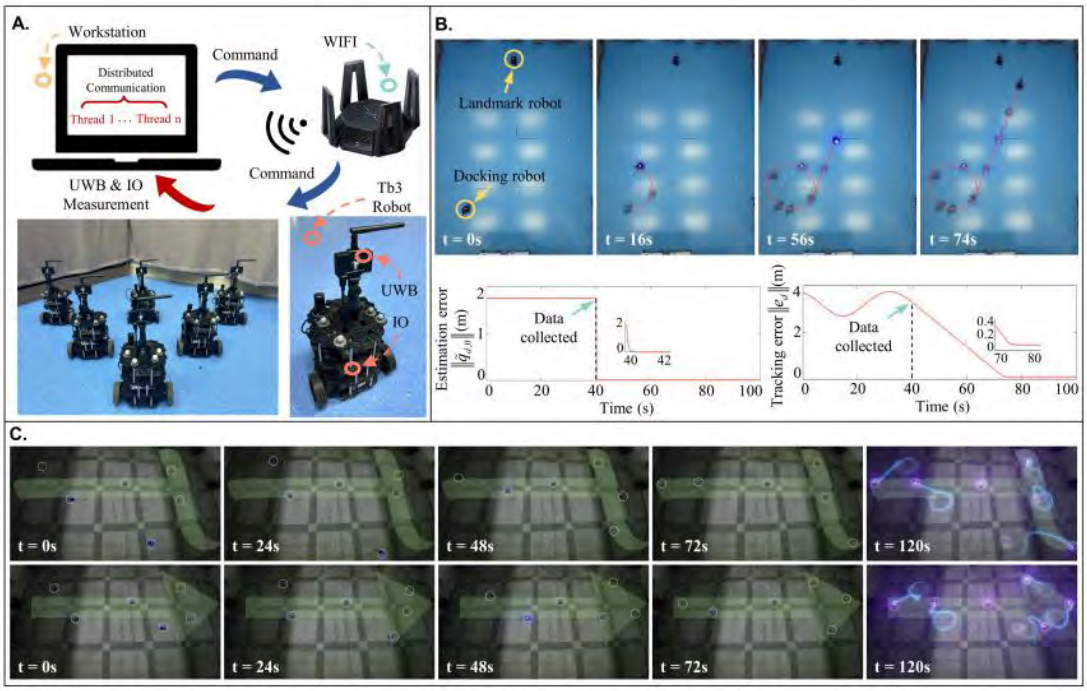

Fig. 8. Indoor and outdoor experiment results **A**. Diagram of the experimental system. **B**. Indoor relative docking experiment results. Here, the estimation error $\tilde{q}_{d,0}$ and tracking error e_d are defined as $\tilde{q}_{d,0}(t) = \hat{p}_{d,0}(t) - (p_0 - p_d(t))$ and $e_d(t) = p_d(t) - p_0 - p^*$. **C**. Outdoor shape formation experiment with a swarm consisted of 6 turtlebot3 robots.

How NOKOV Contributes to the Research

In this experiment, NOKOV motion capture system is used to record the real position of the landmark robot and the docking robot. The trajectory of the docking robot is shown in Fig. 8B.

Citation Lü J, Ze K, Yue S, et al. Concurrent-Learning Based Relative Localization in Shape Formation of Robot Swarms[J]. IEEE Transactions on Automation Science and Engineering, 2025.

Link https://ieeexplore.ieee.org/document/10851292

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CoNi-MPC: Cooperative Non-inertial Frame Based Model Predictive Control

Abstract

This letter presents a novel solution for UAV control in cooperative multi-robot systems, which can be used in various scenarios such as leader-following, landing on a moving base, or specific relative motion with a target. Unlike classical methods that tackle UAV control in the world frame, we directly control the UAV in the target coordinate frame, without making motion assumptions about the target. In detail, we formulate a non-linear model predictive controller of a UAV, referred to as the agent, within a non-inertial frame (i.e., the target frame). The system requires the relative states (pose and velocity), the angular velocity and the accelerations of the target, which can be obtained by relative localization methods and ubiquitous MEMS IMU sensors, respectively. This framework eliminates dependencies that are vital in classical solutions, such as accurate state estimation for both the agent and target, prior knowledge of the target motion model, and continuous trajectory re-planning for some complex tasks. We have performed extensive simulations to investigate the control performance with varying motion characteristics of the target. Furthermore, we conducted real robot experiments, employing either simulated relative pose estimation from motion capture systems indoors or directly from our previous relative pose estimation devices outdoors, to validate the applicability and feasibility of the proposed approach.

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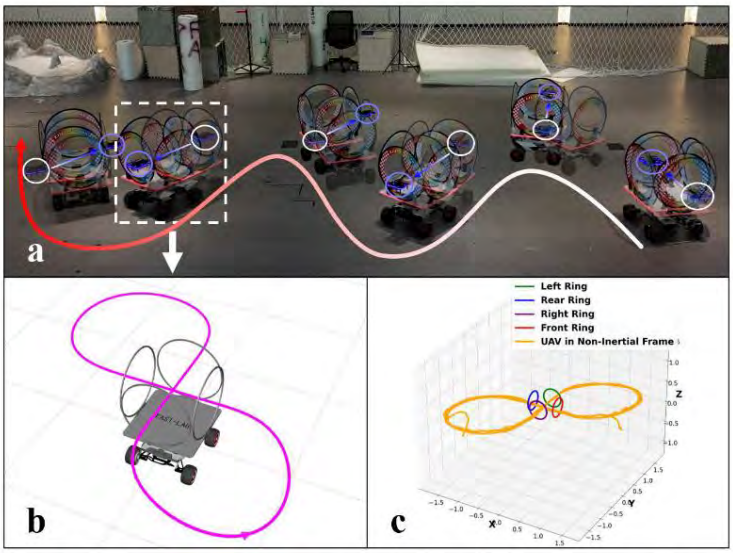

Fig. 11: Rings crossing experiment. The UGV moves with an average speed of 0.15 m/s and a maximal speed of 0.38 m/s while the UAV can cross the ring attached to it.

How NOKOV Contributes to the Research

The relative estimation can be generated directly from CREPES or computed from NOKOV motion capture system for outdoor or indoor experiments respectively.

Citation Zhang B, Chen X, Li Z, et al. Coni-mpc: Cooperative non-inertial frame based model predictive control[J]. IEEE Robotics and Automation Letters, 2023, 8(12): 8082-8089.

Link https://ieeexplore.ieee.org/document/10287548

Connectivity-Preserving Formation Control via Clique-Based Approach Without Prior Assignment

Keywords

Connectivity preservation, dynamic assignment, formation control, maximal clique, multi-agent systems

Abstract

This paper explores information sharing within cliques to enable flexible formation pattern control of networked agents with limited communication range, where each agent is not pre-assigned a fixed point in the pattern and is unaware of the total number of agents. To achieve this, we first present a new representation of formation patterns that enables the agents to reach a consensus on the desired pattern by negotiating formation motion and agent numbers. The problem of continuously assigning each agent a point in the desired pattern is then decomposed into small size problems in terms of δ-maximal cliques, which can be solved in a distributed manner. Furthermore, a maximal clique-based formation controller is employed to ensure that the agents converge to the desired pattern while preserving the connectivity of the communication topology. Simulation results demonstrate that the pattern assembly time of seven agents using the proposed algorithm is reduced by 55.1% compared with a state-of-the-art pre-assigned method, and this improvement tends to amplify with an increasing number of agents. In addition, we conduct a physical experiment involving five robots to verify the ability of the proposed algorithm in terms of formation shape assembly, manipulation, and automatic repair.

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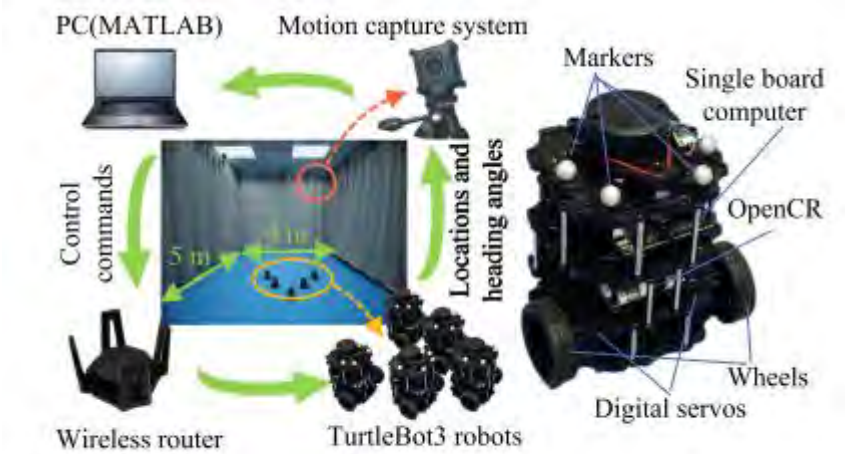

Fig. 7. Physical experiment setup.

How NOKOV Contributes to the Research

The Nokov motion capture system consists of 18 cameras that work together to track the robots'positions and orientations by identifying the markers on top, and it requires a PC to receive real-time data.

Citation Chen J, Zhou R, Zhang Y, et al. Connectivity-Preserving Formation Control via Clique-Based Approach Without Prior Assignment[J]. IEEE Transactions on Network Science and Engineering, 2024.

Link https://ieeexplore.ieee.org/document/10713503

Constructing and Navigating Connected Air Roads: A Safety-Critical Reinforcement Learning Approach for Multi-UAV Systems

Keywords

air road, control barrier function, multi-UAV, reinforcement learning

Abstract

This paper presents an integrated control method in air road navigation for multi-UAV systems, combining an efficient reinforcement learning (RL) controller with a control barrier function (CBF)-based filter that guarantees flight safety. First, an air road construction method based on arbitrary quadrilateral combinations is proposed, which enables flexible air road design. Second, two specific CBFs are designed: an air road CBF which keeps UAVs within designed air roads, and a collision avoidance CBF which prevents collisions between UAVs. Based on the CBF-based filter, the RL controller is allowed to be trained in a simple, single-agent environment, which reduces computational costs and enhances training efficiency. Furthermore, the RL reward is carefully designed, which considers both the stability during movement and the optimality of energy conservation. The performance, safety, and efficiency of the proposed approach are rigorously validated through comprehensive simulations and real-world experiments.

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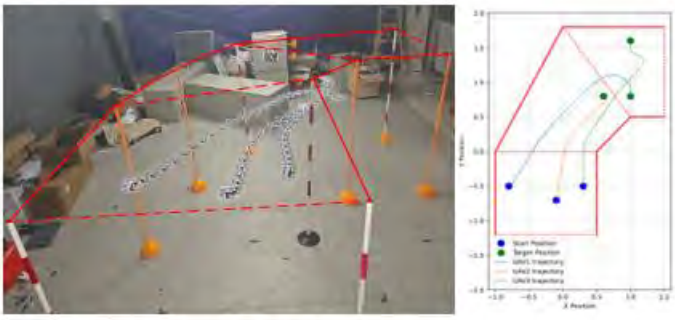

Fig. 6: Trajectories of 3 UAVs navigating through air roads with collision avoidance: left shows the real experiment, and right shows the simulation.

How NOKOV Contributes to the Research

B. Experiment
Limited by venue and equipment. The real experimentis realized with N=3 Crazyflie 2.1 quadcopters in theconnected air road, which includes M= 3 road segments.The multi-UAV system states are measured by the NOKOV Motion Capture System. Al UAVs start at a uniform altitudeof lm with zero initial velocities. The initial positions aregiven as p1 =\[-0.8,-0.5]m,p2 = \[-0.1,-0.7] m,p3=\[0.3,-0.5 m. As shown in Fig. 6, three UAVs realizecollision-free navigation in the air road under integratedcontrollers. It can be obtained from Fig. 7 that proposedCBFs also work well in the real experiment.

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Continuous Implicit SDF Based Any-shape Robot Trajectory Optimization

Keywords

Geometry, Pipelines, Planning, Computational efficiency, Collision avoidance, Robots, Trajectory optimization

Abstract

Optimization-based trajectory generation methods are widely used in whole-body planning for robots. However, existing work either oversimplifies the robot's geometry and environment representation, resulting in a conservative trajectory or suffers from a huge overhead in maintaining additional information such as the Signed Distance Field (SDF). To bridge the gap, we consider the robot as an implicit function, with its surface boundary represented by the zero-level set of its SDF. We further employ another implicit function to lazily compute the signed distance to the swept volume generated by the robot and its trajectory. The computation is efficient by exploiting continuity in space-time, and the implicit function guarantees continuous collision evaluation even for nonconvex robots with complex surfaces. We also propose a trajectory optimization pipeline applicable to the implicit SDF. Simulation and real-world experiments validate the high performance of our approach for arbitrarily shaped robot trajectory optimization.

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Fig. 6: The real-world indoor experiment: The quadrotor must traverse three consecutive circles while precisely avoiding nearby obstacles. We highlight the most critical frames when the robot is closest to the obstacles.

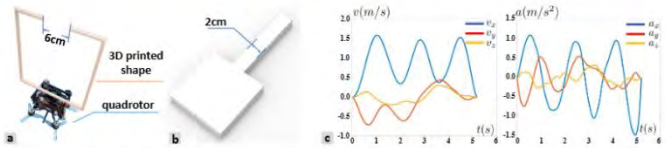

Fig. 7: The UAV platform and the obstacle in the experiment are shown in Fig.a and Fig.b.The velocity and acceleration of the drone in the real experiment are shown in Fig.c.

How NOKOV Contributes to the Research

We conduct a real-world experiment with the motion capture NOKOV system. Fig.7a shows the quadrotor robot in our experiment. We deliberately install a structure on the robot to give it a complex shape. We hang the obstacle shown in Fig.7b inside a ring so that the robot has to cross the ring from the correct position to ensure that it does not collide.

Citation T. Zhang, J. Wang, C. Xu, A. Gao and F. Gao, "Continuous Implicit SDF Based Any-Shape Robot Trajectory Optimization," 2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Detroit, MI, USA, 2023, pp. 282-289, doi: 10.1109/IROS55552.2023.10342104.

Link https://ieeexplore.ieee.org/document/10342104

Continuous Occupancy Mapping in Dynamic Environments Using Particles

Keywords

Mapping; Aerial Systems: Perception and Autonomy; Collision Avoidance; Dynamic Environment;

Abstract

Dynamic occupancy maps were proposed in recent years to model the obstacles in dynamic environments. Among these maps, the particle-based map offers a solid theoretical basis and the ability to model complex-shaped obstacles. Current particle-based maps describe the occupancy status in discrete grid form and suffer from the grid size problem, namely: large grid size is unfavorable for path planning while small grid size lowers efficiency and causes gaps and inconsistencies. To tackle this problem, this paper generalizes the particle-based map into continuous space and builds an efficent 3D local map. A dual-structure subspace division paradigm, composed of a voxel subspace division and a novel pyramid-like subspace division, is proposed to propagate particles and update the map efficiently with the consideration of occlusions. The occupancy status of an arbitrary point can then be estimated with the cardinality expectation. To reduce the noise in modeling static and dynamic obstacles simultaneously, an initial velocity estimation approach and a mixture model are utilized. Experimental results show that our map can effectively and efficiently model both dynamic obstacles and static obstacles. Compared to the state-of-the-art grid-form particle-based map, our map enables continuous occupancy estimation and substantially improves the performance in different resolutions. We also deployed the map on a quadrotor to demonstrate the bright prospect of using this map in obstacle avoidance tasks of small-scale robotics systems.

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How NOKOV Contributes to the Research

The velocity estimation experiments were conducted with the data collected in an indoor testing field with the Nokov motion capture system.

Citation G. Chen, W. Dong, P. Peng, J. Alonso-Mora and X. Zhu, "Continuous Occupancy Mapping in Dynamic Environments Using Particles," in IEEE Transactions on Robotics, vol. 40, pp. 64-84, 2024, doi: 10.1109/TRO.2023.3323841.

Link https://ieeexplore.ieee.org/document/10285872

Continuous-time Gaussian Process Trajectory Generation for Multi-robot Formation via Probabilistic Inference

Abstract

In this paper, we extend a famous motion planning approach GPMP2 to multi-robot cases, yielding a novel centralized trajectory generation method for the multi-robot formation. A sparse Gaussian Process model is employed to represent the continuous-time trajectories of all robots as a limited number of states, which improves computational efficiency due to the sparsity. We add constraints to guarantee collision avoidance between individuals as well as formation maintenance, then all constraints and kinematics are formulated on a factor graph. By introducing a global planner, our proposed method can generate trajectories efficiently for a team of robots which have to get through a width-varying area by adaptive formation change. Finally, we provide the implementation of an incremental replanning algorithm to demonstrate the online operation potential of our proposed framework. The experiments in simulation and real world illustrate the feasibility, efficiency and scalability of our approach.

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How NOKOV Contributes to the Research

We test the proposed framework with a team of quadrotorson three common scenarios: formation maintenance, replanning for a changed destination and adaptive formation change for moving through a width-varying area. Experiments in the real world are conducted with a group of Crazyflie nano- quadrotors flying under the supervision of a NOKOV motion capture system.

Citation Guo S, Liu B, Zhang S, et al. Continuous-time gaussian process trajectory generation for multi-robot formation via probabilistic inference[C]//2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2021: 9247-9253.

Link https://ieeexplore.ieee.org/abstract/document/9636573

Cooperative Localization and Mapping Based on UWB/IMU Fusion Using Factor Graphs

Keywords

Data fusion, factor graph, localization, multisource heterogeneity, multitarget collaboration

Abstract

In complex and unknown environments, achieving precise localization and real-time mapping stands as a critical requirement for agent navigation and scene comprehension. However, conventional localization methods, which rely on single sensors such as inertial measurement units (IMUs) or ultra-wideband (UWB) sensors, often face challenges in maintaining high precision within these intricate settings. Consequently, the task of achieving accurate self-localization and constructing topological maps becomes increasingly daunting. To tackle this challenge, we introduce a collaborative localization and mapping approach that harnesses data from both IMU and UWB sensors. We employ factor graphs as the representation model, treating observations, states, and constraints as factors within the graph. The IMU provides vital attitude and acceleration information, while the UWB sensor contributes valuable distance observations. Through the maximization of posterior probability, we estimate the agent's position and create the map. Our comprehensive evaluations conducted in physical environments conclusively demonstrate the effectiveness of our method in achieving accurate localization and mapping.

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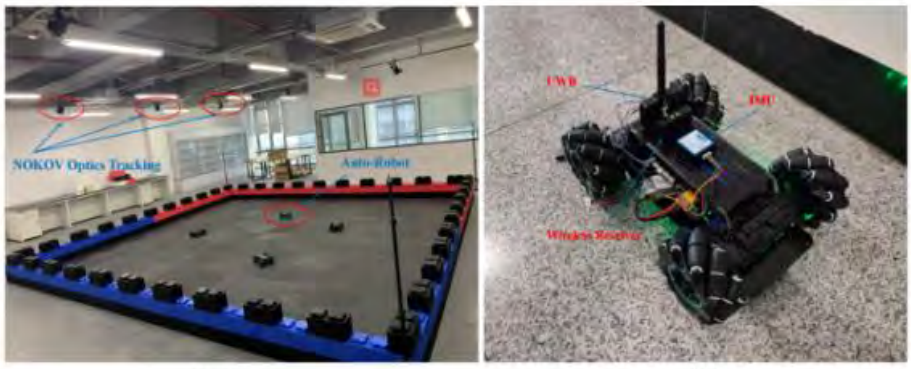

(a) (b)

Fig. 8. (a) Scene for physical experiment. (b) Auto-robot and sensors used for the test.

How NOKOV Contributes to the Research

The sensor informa-tion and position data are collected during the experiments.The ground truth is captured by the NOKOV optics motiontracking system \[29]. The IMU provides motion data for theentities, while the UWB sensors are used to estimate jointfactors for multiagent cooperative localization, sampling at100 and 10 Hz, respectively. Furthermore, the trajectory paths and localization errors are considered to evaluate the algorithm's performance.

Citation Wang R, Xu C, Li R, et al. Cooperative localization and mapping based on UWB/IMU fusion using factor graphs[J]. IEEE Sensors Journal, 2023, 24(14): 21931-21940.

Link https://ieeexplore.ieee.org/abstract/document/10269786

Cooperative Localization for Multi-Agents Based on Reinforcement Learning Compensated Filter

Keywords

Multi-agent reinforcement learning, nonlinear filtering, value decomposition, cooperative localization

Abstract

In modern navigation and positioning systems, accurate location information is crucial for ensuring system performance and user experience. Particularly, in scenarios involving the use of multiple agents such as robots and drones for rescue operations in unknown complex environments, accurate localization is fundamental for subsequent actions. However, traditional filtering-based localization algorithms may exhibit suboptimal performance and are sensitive to initial estimates and system noise. To address these issues, this paper proposes a multi-agent collaborative localization algorithm based on reinforcement learning compensation filtering to tackle localization problems in complex environments and improve the robustness and accuracy. Specifically, this paper introduces a value decomposition-based reinforcement learning network for filtering compensation to reduce overall localization error and address the credit allocation problem in multi-agent reinforcement learning. The main contributions of this paper are as follows: Firstly, a local localization estimation method based on reinforcement learning compensation Extended Kalman Filter (EKF) is proposed, which further corrects the results of the EKF algorithm and eliminates initial estimation errors. Secondly, a global collaborative localization estimation algorithm (MARL_CF) based on credit allocation in multi-agent reinforcement learning is proposed, which maximizes the reduction of overall localization error through information sharing and global optimization. Finally, the effectiveness of the proposed algorithms is validated through both numerical simulation and physical experiments. The results demonstrate that the proposed MARL_CF significantly improve the accuracy and robustness of localization in complex environments.

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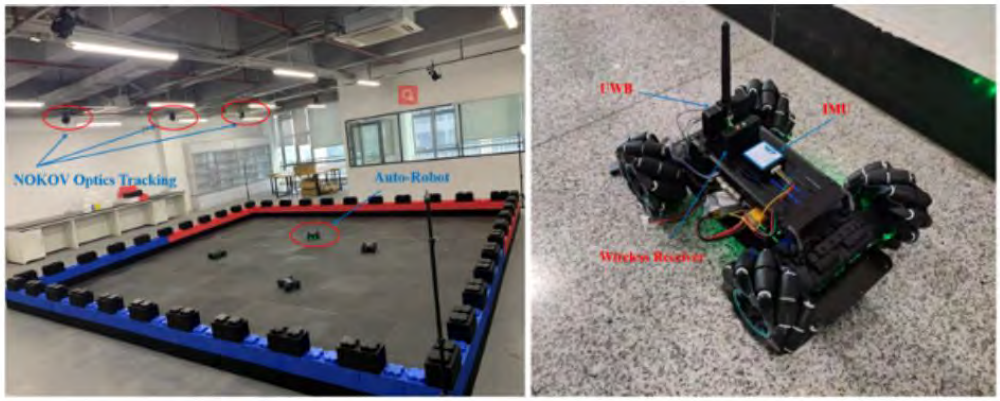

Fig. 9. **Left:** The scene for physical experiment. **Right:** The auto-robot and sensors used for the test.

How NOKOV Contributes to the Research

hese robots operated in two modes: random walk and regularmotion, for a duration of 100 seconds each. Ground truth data was captured using the NOKOV optics motion trackingsystem . Subsequently, the trajectory and localization errors of the agents were analyzed to evaluate the algorithm's performance.

Citation Wang R, Xu C, Sun J, et al. Cooperative localization for multi-agents based on reinforcement learning compensated filter[J]. IEEE Journal on Selected Areas in Communications, 2024, 42(10): 2820-2831.

Link https://ieeexplore.ieee.org/abstract/document/10557677

Cooperative Obstacle Avoidance of Unmanned System Swarm via Reinforcement Learning Under Unknown Environments

Keywords

Obstacle avoidance, reinforcement learning, unknown environment, unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), unmanned system swarm

Abstract

The deployment of unmanned system swarm, especially unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs), has gained significant attention in various applications. However, the effective navigation of unmanned system swarm in unknown and dynamic environments remains a formidable task. To address this challenge, a novel approach that combines reinforcement learning and artificial potential field (APF) methods is presented in this article. The proposed framework utilizes the double deep Q-network (DDQN) with a prioritized experience replay mechanism to train the actions of the virtual leader, which leads to the motion of the whole unmanned system swarm. In addition, the APF method is also applied to each unmanned system in swarm to achieve distributed obstacle avoidance. By training virtual leader to guide all individuals, the unmanned system swarm can adapt and navigate safely in unfamiliar surroundings. Simulations and experiments validate the proposed method, demonstrating enhanced obstacle avoidance and autonomous navigation for the swarm.

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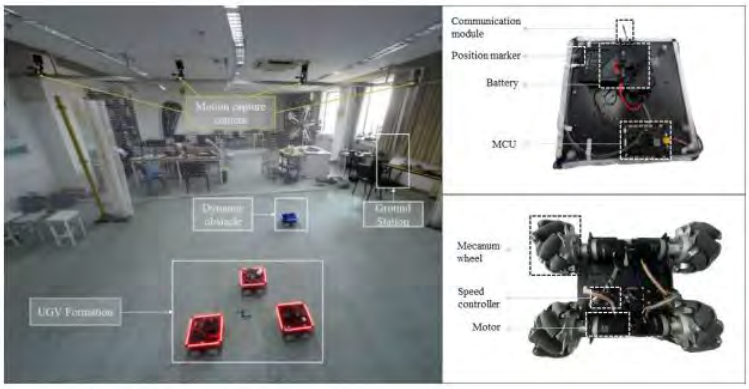

Fig. 22. Experiment scenario and omnidirectional UGVs.

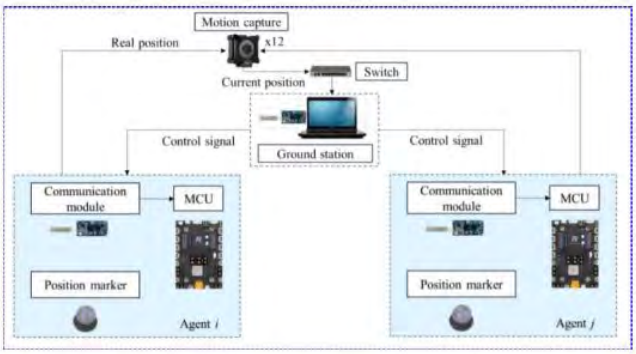

Fig. 23. Hardware structure of the omnidirectional UGV swarm.

How NOKOV Contributes to the Research

In addition to simulation experiments, physical experimentsare also conducted to validate the effectiveness of our proposed algorithm. As shown in Fig.22, the experiment platform consists of NOKOV motion capture positioning system, ground station, and omnidirectional-wheeled vehicle. Detailsof hardware structure shown in Fig.23 are provided as follows.

Citation Zhang X, Zong H, Wu W. Cooperative obstacle avoidance of unmanned system swarm via reinforcement learning under unknown environments[J]. IEEE Transactions on Instrumentation and Measurement, 2024.

Link https://ieeexplore.ieee.org/abstract/document/10816318

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Cooperative Path Planning for Multiplayer Reach-Avoid Games under Imperfect Observation Information

Abstract

This article investigates a reach-avoid game and proposes a cooperative path planning algorithm for a target–pursuers (TP) coalition to capture an evader. In the game, the target aims to bait and escape from the evader, and the pursuer aims to capture the evader. Due to imperfect observations, the TP coalition has uncertain information of the evader's state, while the evader is assumed to have perfect observation. The game model is constructed by formulating the optimization problems for each player in a receding horizon fashion. Then, to counter the evader effectively, the TP coalition constructs a virtual evader using the belief information from a Kalman filter. And a chance constraint optimization problem is constructed to predict the virtual evader's trajectory under uncertainties. The TP coalition can capture the actual evader by generating a robust counter-strategy against the virtual evader with a chance constraint feasible set. Next, to compute the Nash equilibrium of the TP coalition's subjective game, an iterative algorithm is designed that combines the iterative best response and the distributed alternating direction method of multiplier algorithms. Finally, the effectiveness of the algorithm is validated through simulations and experiments.

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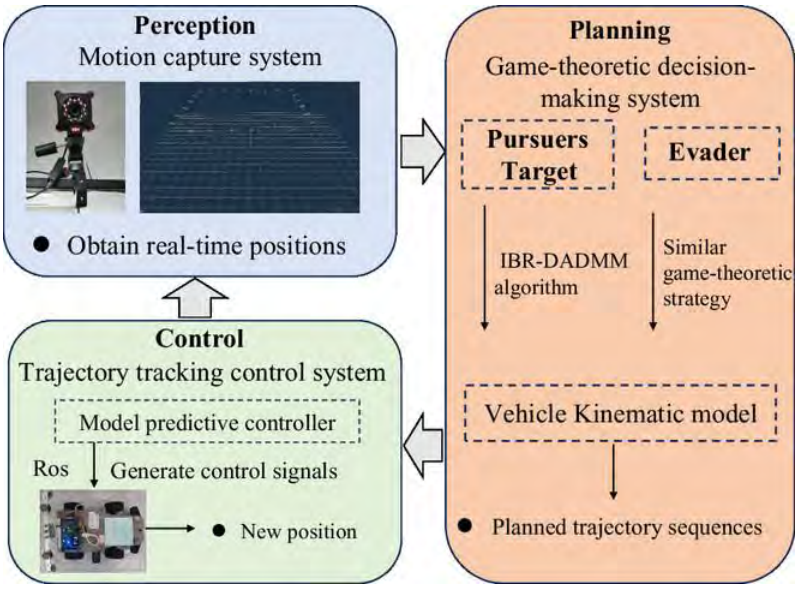

How NOKOV Contributes to the Research

In this section, we use experiments to verify the effectiveness ofthe proposed algorithm. The hardware platform is built withthree main modules, the game system, the NOVOK systemand the workstation. In the game system, four autonomousground vehicles (AGVs)represent the pursuers, the target, and the evader. Therefore, all the 3D models discussed in thisarticle need to be downscaled into 2D models here. In the NOKOV system, 24 motion capture cameras are used to capturethe motion states of all vehicles. In the workstation, the motioncapture map is preconstructed, the motion planning and contro!modules are run on an on-board Nvidia TX1 computer,The vehicles receive control signals via the ROS commandcmd vel.

Citation Fang H, Chen Y, Yi P. Cooperative Path Planning for Multiplayer Reach-Avoid Games under Imperfect Observation Information[J]. Advanced Intelligent Systems, 2024, 6(9): 2300794.

Link https://onlinelibrary.wiley.com/doi/10.1002/aisy.202300794

Cost-Effective Swarm Navigation System via Close Cooperation

Keywords

Multi-robot systems, cooperating robots, motion and path planning, heterogeneous system

Abstract

Multi-robot system is desired to achieve global cost-efficiency by fully utilizing individual advantages. For example, leveraging unmanned aerial vehicles' (UAVs') agility for inspection and ground vehicles' (UGVs') capability for heavy-duty tasks. Coordinating the motion of multiple robots smartly is complex and it becomes more challenging when robots in the swarm are not equipped with sufficient sensors for environmental perception (e.g. in our case only one robot has a depth camera). In this letter, we propose a tightly coupled systematic framework to navigate a swarm composed of UAV and UGVs in unknown scenes. The system has only one depth camera with a field of view for environmental perception. We fully explore the cooperation between robots by proposing a Sequential Exploration and Aiding Localization (SEAL) planning strategy for the UAV and a Collision-Adaptive Trajectory (CAT) optimization for UGVs. The UAV assists UGVs' localization with relative pose estimation and own global localization, meanwhile, it focuses on exploration to provide UGVs with abundant environmental information. The UGV team can navigate safely and autonomously in obstacle-rich environments and even maintain formations with only the wheel odometer and UAV's assistance using CAT optimization. Our method is validated both in simulations and real-world experiments indoors and outdoors.

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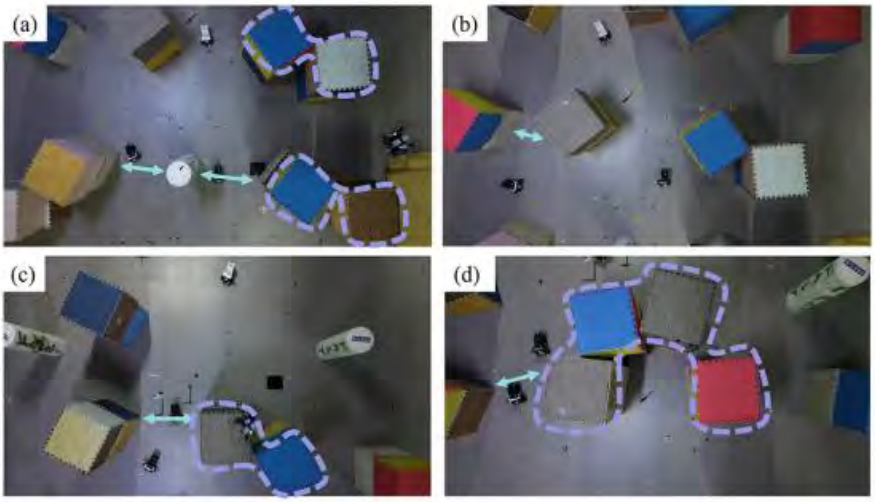

Fig. 12. Indoor scene (2)-(4) in more complex environments, with narrow gaps (green double arrow) and concave obstacles (purple dotted region). (a),(b) correspond to the scene (2), while (c) and (d) correspond to the scene (3) and (4) respectively.

How NOKOV Contributes to the Research

To validate our system, we conduct two sets of real-worldexperiments, indoors and outdoors. In all real-world tests, weadopt Vins-FUSION\[21]for UAV's state estimation with an In-tel RealSense Depth Camera D435. The relative pose estimationis obtained through two solutions, the NOKOV Motion Capture System (MCS) and our previous work, CREPES\[1]for indoorand outdoor respectively. Each agent in the swarm runs theiralgorithms on an Intel Core i7-1165G7 CPU.

Citation Chen N, Li Z, Quan L, et al. Cost-Effective Swarm Navigation System via Close Cooperation[J]. IEEE Robotics and Automation Letters, 2024, 9(11): 9343-9350.

Link https://ieeexplore.ieee.org/document/10545578

COVER: cross-vehicle transition framework for quadrotor control in air-ground cooperation

Keywords

Motion control, Multiple non-inertial frames, Air-ground cooperation, Trajectory optimization, Model predictive control

Abstract

UAV transitions across UGVs enable diverse air-ground cooperation (AGC) applications, such as cross-vehicle landing, delivery, and rescue. However, achieving precise and efficient transitions across multiple moving UGVs without prior knowledge of their trajectories remains highly challenging. This paper proposes COVER, a cross-vehicle transition framework for quadrotor control in AGC scenarios. In COVER, the UAV is directly controlled in UGVs' body frames as non-inertial frames, thus eliminating all dependencies in the world frame. Each transition process is divided into three stages: the initial stage, transition stage, and final stage, with pre-set stage transition points and stage-varying system states. Then, an optimal reference trajectory is generated at each stage by solving a non-linear programming (NLP) problem. The effect of the target UGV's rotation on the initial relative velocity is eliminated to obtain a dynamically feasible and smooth transition reference trajectory. Finally, we design a stage-adaptive model predictive control (SAMPC) method, proposing a novel MPC position reference mode to avoid indirect routes at the transition stage. The SAMPC method effectively mitigates the flight instability caused by reference frame transition and eliminates the effect of reference frame rotation at the transition stage. And it can flexibly adapt to accurate requirements at the final stage by switching position reference mode and adjusting cost weights. Simulation benchmarks and extensive real-world experiments validate that our approach can achieve smooth, short-distance, and accurate cross-vehicle operations.

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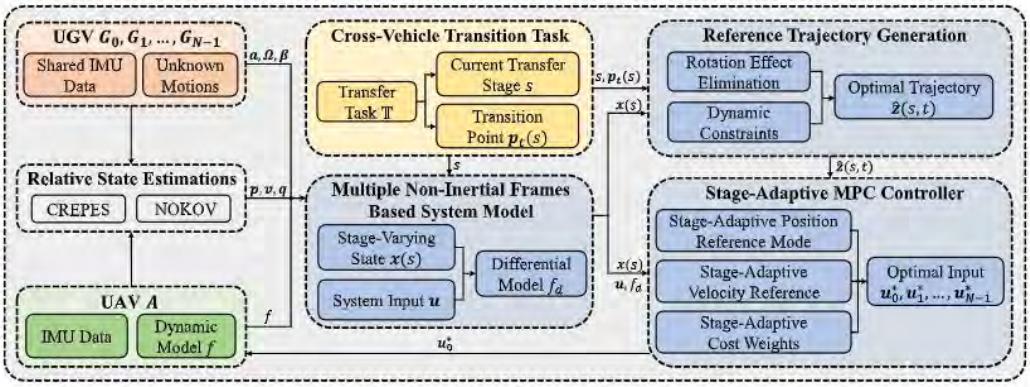

Fig. 4 Overview of the proposed framework

How NOKOV Contributes to the Research

The proposed framework overview is illustrated in Fig. 4. For a system consisting of one UAV and N UGVs, given a transition task T, we first utilize CREPES (Xun et al., 2023) or NOKOV motion capture system to estimate relative states between the UAV and each UGV.
Relative state esti-mations between the UAV and UGVs are computed from the NOKOV motion capture system, and the IMU data of UGVs is shared with the UAV through WiFi.

Citation Ren Q, Xu M, Zhang M, et al. COVER: cross-vehicle transition framework for quadrotor control in air-ground cooperation[J]. Autonomous Robots, 2025, 49(3): 23.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001562585500001

CSVO: Complementary-Pathway Spatial-Enhanced Visual Odometryfor Extreme Environments with Brain-inspired Vision Sensors

Abstract

Visual Odometry (VO) estimates the pose and motion trajectory of the camera based on visual input, serving as a fundamental technique for robotic positioning and navigation. However, existing VO methods face challenges in visual degradation in extreme environments, e.g., high dynamic range or fast-motion conditions. Although event-based sensing schemes offer partial solutions to this problem, they are limited by unstable features and noise. Recently, a novel brain-inspired vision sensor, Tianmouc, has been reported, incorporating two complementary pathways: a cognition-oriented pathway (COP) for precise color intensity and an action-oriented pathway (AOP) for fast spatiotemporal sensing, considered a promising visual input for VO tasks. Here, we develop Complementary Pathway Spatial Enhanced Visual Odometry (CSVO) to cope with extreme scenarios by fusing the COP and AOP information of Tianmouc. To leverage the dynamic range expansion brought about by dual-pathway fusion, as well as the low-latency spatial difference data in AOP to address high-speed motion, we design an asynchronous dual-pathway feature encoder considering synchronous multimodal fusion and asynchronous cross-modal feature matching. To train and evaluate CSVO, we transform two conventional VO datasets, TartanAir and Apollo, to Tianmouc modality through simulation and collect a real-world Tianmouc-VO dataset in challenging scenes. Our results demonstrate state-of-the-art performance over existing methods on these datasets. Our work sheds light on the generalizability of agents working in extreme scenarios.

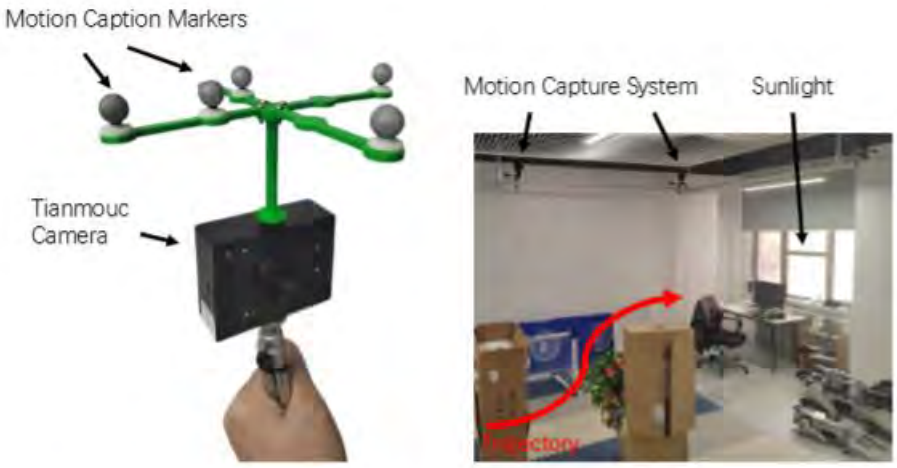

Fig. 4. Data collection scenes of the Tianmouc-VO dataset. Direct sunlight and rapid motion are deliberately introduced during the data recording process to create data under extreme environments.

How NOKOV Contributes to the Research

The recording system for Tianmouc-VO comprises a cam-era outfitted with Tianmouc and a motion capture devicefeaturing eight cameras (NOKOV Mars1.3HW). This camerais secured with a 3D-printed mount that includes five motioncapture markers, ensuring high-precision camera poses. Theprecision of this motion capture system is specified as± 0.3mm, with its operational frequency set to 350 Hz. Therecording area is delineated as5m ×5m. The lens attached tothe Tianmouc camera is described as 2.8 mm.

Citation Y. Lin, Z. Zhang, Y. Chen, T. Wang and R. Zhao, "CSVO: Complementary-Pathway Spatial-Enhanced Visual Odometry for Extreme Environments with Brain-Inspired Vision Sensors," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 9028-9035, doi: 10.1109/IROS60139.2025.11246288.

Link https://ieeexplore.ieee.org/document/11246288

Data-driven flocking behavior of multi-agent systems under uncertain environments

Keywords

Multi-agent systems, Flocking behavior, Data-driven control, Control barrier functions

Abstract

In numerous practical application scenarios, the collaborative control tasks of multi-agent systems are challenged by the fact that the dynamic characteristics and environmental conditions of agents (such as robots, drones, and autonomous vehicles, etc.) are often unknown. In this paper, an approach based on data-driven learning control barrier functions is proposed to investigate the flocking control issue of multi-agent systems with unknown dynamics under uncertain environments. The verification of the flocking behavior in multi-agent systems is facilitated by flocking error system, upon which a data-driven flocking controller employing pseudo partial derivatives is constructed. Secondly, a data-driven learning control barrier functions scheme based on the idea of Gaussian process is established for multi-agent systems under uncertain environment, which can ensure the safety of agents and eliminate the dependence of traditional control barrier functions method on the system model. Moreover, two zeroing control barrier functions are provided to ensure the safety and low uncertainty of the agents, respectively, so as to achieve system convergence. Finally, the effectiveness of theoretical results is verified through numerical simulation and experiments.

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Fig. 11. Multi-UAV working environment. The environment primarily consists of uncertain obstacles, UAV swarm, and motion capture system.

How NOKOV Contributes to the Research

5.3. Example 3
Based on the above simulation, we build an indoor multi-UAVs verification platform (see Fig, 10) through NOKOV Motion Capture System \[43]. The system consists of 12 Mars4H lenses (for acquiring agent information, Fig. 10(a)), along with drones(Fig. 10(b)) and distance sensors (for obtaining distances to obstacles, Fig. 10(c). A minimum agent distance of 2 > 500mmenforced to prevent dangerous proximity during flocking. For precision, all units in this section are consistently expressed inmillimeters.

Citation Yan S, Shi L, Zhu P, et al. Data-Driven Flocking Behavior of Multi-Agent Systems Under Uncertain Environments[J]. Applied Mathematical Modelling, 2025: 116449.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001585383500001

Decentralized Planning for Car-Like Robotic Swarm in Cluttered Environments

Keywords

Robot kinematics, Wireless networks, System recovery, Real-time systems, Robustness, Planning, Trajectory

Abstract

Robot swarm is a hot spot in robotic research community. In this paper, we propose a decentralized framework for car-like robotic swarm which is capable of real-time planning in cluttered environments. In this system, path finding is guided by environmental topology information to avoid frequent topological change, and search-based speed planning is leveraged to escape from infeasible initial value's local minima. Then spatial-temporal optimization is employed to generate a safe, smooth and dynamically feasible trajectory. During optimization, the trajectory is discretized by fixed time steps. Penalty is imposed on the signed distance between agents to realize collision avoidance, and differential flatness cooperated with limitation on front steer angle satisfies the non-holonomic constraints. With trajectories broadcast to the wireless network, agents are able to check and prevent potential collisions. We validate the robustness of our system in simulation and real-world experiments. Code will be released as open-source packages.

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How NOKOV Contributes to the Research

We conduct real-world experiments in a 3m × 8m environment, where three car-like robots move from one side to the other. Each robot is equipped with an NVIDIA Jetson Nano as the onboard processor and a single-line lidar with a 3m sensing range, which is equal to the horizon of locally planned trajectories. Localization is done by the NOKOV motion capture system.

Citation C. Ma et al., "Decentralized Planning for Car-Like Robotic Swarm in Cluttered Environments," 2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Detroit, MI, USA, 2023, pp. 9293-9300, doi: 10.1109/IROS55552.2023.10342360.

Link

https://ieeexplore.ieee.org/search/searchresult.jsp?newsearch=true&queryText=Decentralized%20Planning%20for%20Car-Like%20Robotic%20Swarm%20in%20Cluttered%20Environments

Deep Reinforcement Learning based Multi-target Coverage with Connectivity Guaranteed

Keywords

Multi-target coverage; multi-robot system; connectivity maintenance; deep reinforcement learning;

Abstract

Deriving a distributed, time-efficient, and connectivity guaranteed coverage policy in multi-target environment poses huge challenges for a multi-robot team with limited coverage and limited communication. In particular, the robot team needs to cover multiple targets while preserving connectivity. In this paper, a novel deep reinforcement learning based approach is proposed to take both multi-target coverage and connectivity preservation into account simultaneously, which consists of four parts: a hierarchical observation attention representation, an interaction attention representation, a two-stage policy learning, and a connectivity guaranteed policy filtering. The hierarchical observation attention representation is designed for each robot to extract latent features of the relations from its neighboring robots and the targets. To promote the cooperation behavior among the robots, the interaction attention representation is designed for each robot to aggregate information from its neighboring robots. Moreover, to speed up the training process and improve the performance of the learned policy, the two-stage policy learning is presented using two reward functions based on algebraic connectivity and coverage rate. Furthermore, the learned policy is filtered to strictly guarantee connectivity based on a model of connectivity maintenance. Finally, the effectiveness of the proposed method is validated by numerous simulations. Besides, our method is further deployed to an experimental platform based on quad-rotor unmanned aerial vehicles (UAVs) and omni- directional vehicles. The experiments illustrate the practicability of the proposed method.

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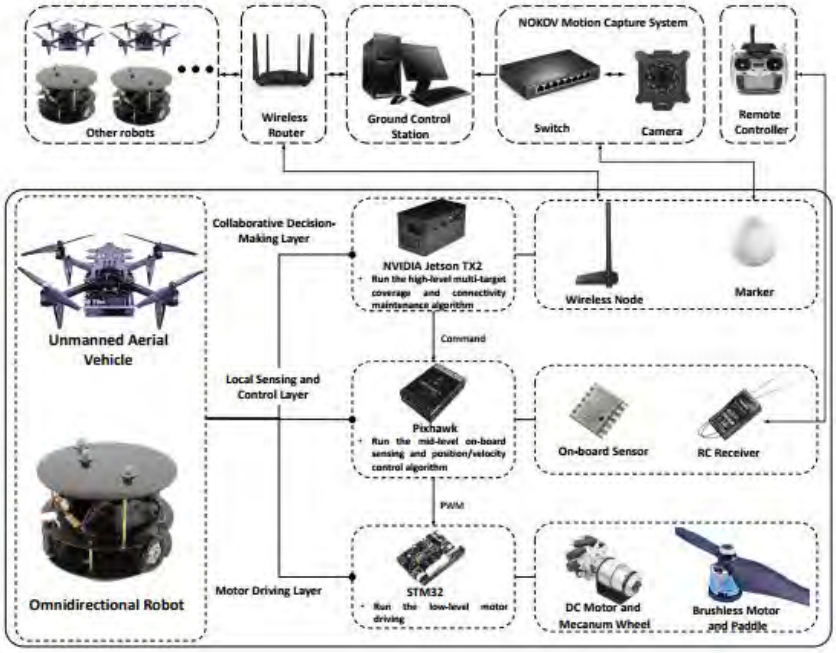

Fig. 6. Architecture of unmanned system consisting of quad-rotor UAV and omnidirectional vehicle.

How NOKOV Contributes to the Research

NOKOV motion capture system is used to calculate the positions and velocities of the mobile robots.

Citation Wu S, Pu Z, Qiu T, et al. Deep-reinforcement-learning-based multitarget coverage with connectivity guaranteed[J]. IEEE Transactions on Industrial Informatics, 2022, 19(1): 121-132.

Link https://ieeexplore.ieee.org/abstract/document/9738445

Density-Based Probabilistic Graphical Models for Adaptive Multi-Target Encirclement of UAV Swarm

Keywords

Probabilistic graphical model (PGM), adaptive multi-target encirclement, autonomous aerial vehicles, density

Abstract

Multi-target encirclement with autonomous aerial vehicle (AAV) swarms is critical for military and civilian applications such as surveillance and disaster response. Existing methods face limitations in adaptability, primarily due to their reliance on predefined formations, excessive communication requirements, and poor scalability. To address these challenges, we propose a density-based probabilistic graphical model (DB-PGM) to achieve adaptive multi-target encirclement. DB-PGM models the cooperative encirclement of multiple targets through a scalable perception-decision graph structure, where node probabilities are dynamically estimated using a local spatial density-driven parameter estimation method. By integrating Maximum A Posteriori inference with real-time perception updates, the system adaptive adjusts encirclement strategies without predefined formations. This approach enables AAVs to achieve adaptive multi-target encirclement based on evolving spatial density distributions and target movements, ensuring adaptability in complex and dynamic environments. Simulations and real-world experiments validate the effectiveness, adaptability, and robustness of the DB-PGM approach, demonstrating its ability to successfully encircle multiple evasive targets in cluttered environments.

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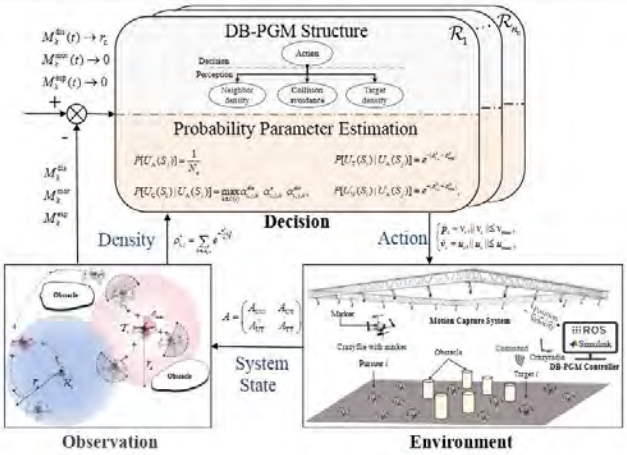

Fig. 2. Overview of the proposed density-based probability graph model (DB-PGM) approach for multi-target encirclement. Each UAV updates its DB-PGM by perceiving the target, neighbors, and obstacle information. This information is used to update the probability parameters of the DB-PGM. Based on these updates, decisions are made using probabilistic inference to infer the joint probabilities of the nodes. The resulting actions are executed to adjust the swarm UAVs' behavior, thereby accomplishing closed-loop control.

How NOKOV Contributes to the Research

This experiment evaluates the fault tolerance of the pro-posed approach by testing whether remaining UAVs can com-plete encirclement tasks despite partial malfunctions, usingup to 10 physical quadrotors. As shown in Fig. 2, CrazyflieUAVs were tracked via a 90 Hz NOKOV motion capture system, with decentralized control executed through a ROS-Simulink framework. Closed-loop commands were transmittedvia Crazyradio modules.

Citation Huang Y, ang X, Yan C, et al. Density-Based Probabilistic Graphical Models for Adaptive Multi-Target Encirclement of UAV Swarm[J]. IEEE Robotics and Automation Letters, 2025.

Link https://ieeexplore.ieee.org/document/11051244

Design and Control of TAWL—A Wheel-Legged Rover With Terrain-Adaptive Wheel Speed Allocation Capability

Keywords

Legged robot; planetary rover; terrain adaptive capability; wheel speed allocation; wheeled robot.

Abstract

This article presents the design, control, and implementation of a novel four-legged rover for planetary exploration. A novel active-passive coupled leg mechanism is proposed for the design of the planetary rover. Then, based on the design of the actuator and leg mechanism, the novel wheel-legged robotic system is developed. Furthermore, the kinematic model of the robot is established and then a kinematics-based control strategy is presented, incorporating roll-and-pitch control, contact force control, wheel speed allocation, and steering modules. Experiments are carried out on regular indoor terrain and irregular outdoor terrain. The variations of rover attitude angles and contact forces in regular terrain decrease by more than 90% and 60%, respectively. In the outdoor environment, rover attitude angles are regulated within 1o and variations of contact forces are reduced by more than half. In addition, the proposed control strategy decreases the slippage on hard unstructured terrain by almost half. Finally, the robustness and failure responses of the robot are investigated, which are also verified by simulations and experiments.

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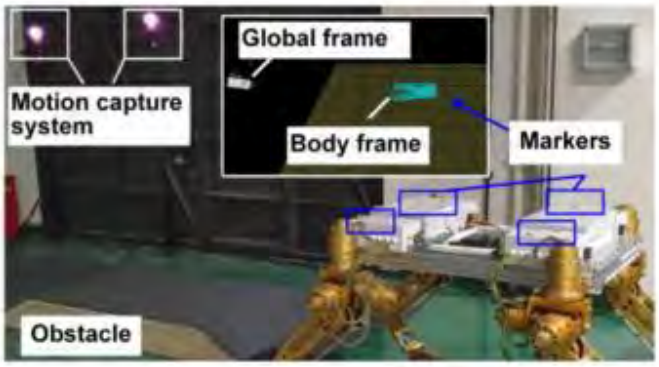

Fig. 15. Slippage experiments.

How NOKOV Contributes to the Research

Here, they are measured in real-time by the NOKOV visual motion capture system pictured in Fig. 15, which includes five cameras. Serval markers bonded on the body of the rover are used to establish the body frame in the world coordinate system.

Citation He J, Sun Y, Yang L, et al. Design and control of TAWL—a wheel-legged rover with terrain-adaptive wheel speed allocation capability[J]. IEEE/ASME Transactions on Mechatronics, 2022, 27(4): 2212-2223.

Link https://ieeexplore.ieee.org/abstract/document/9794482

Design and Implementation of Experimental Platform for Multi-agent System

Keywords

experimental platform, ROS, MATLAB/Simulink, multi-agent, UAV, UGV

Abstract

To achieve programmability, modularity, cost-effectiveness, and practical effectiveness in multi-agent body experimental processes, we propose an experimental control platform for multi-agent body robots based on ROS (Robot Operating System) and MATLAB/Simulink in this paper. Firstly, we discuss the experimental platform used in this study, which integrates NOKOV motion capture equipment and the Gazebo simulator. Information is transferred through the ROS-Simulink information bridge, allowing users to focus on designing control algorithms and interacting with experimental information during use. Furthermore, we provide various modeling and simulation examples under the designed experimental platform, including different types of multi-agent bodies such as UAV and UGV, different UGV models including the Turtle model in ROS and Mecanum wheel simulation model, and various trajectory tracking algorithms such as Pure Pursuit and self-designed tracking algorithms. Through simulating and controlling experimental examples, we have discovered that correct modeling of the multi-agent body under the experimental platform allows the model code built on the Simulink platform to be directly transferred to the ROS platform for implementation or cross-platform control. This significantly enhances the efficiency of developers in solving practical engineering problems and generates high utilization value and positive economic benefits.

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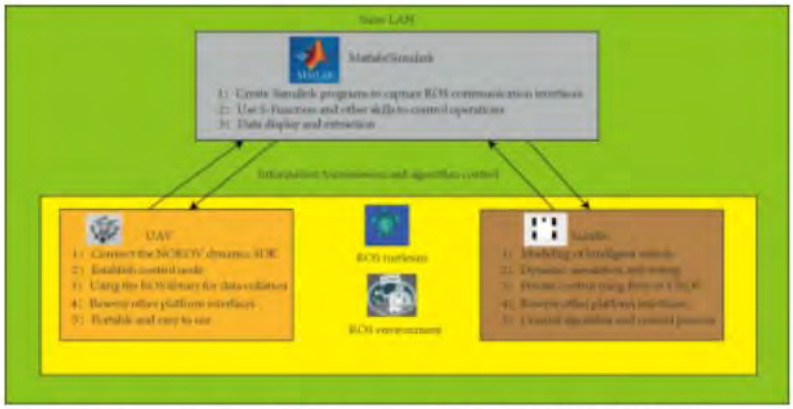

Fig. 1. Information interaction diagram of ROS-NOKOV-GAZEBO

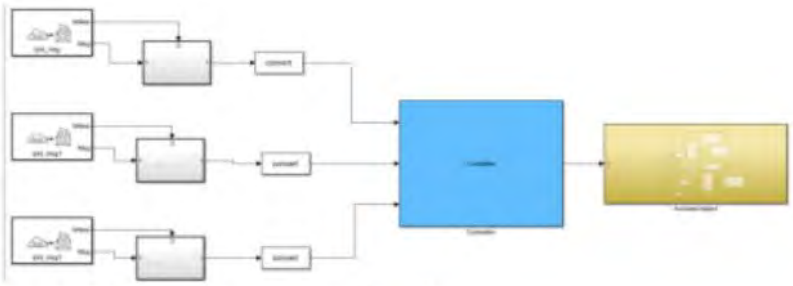

Fig. 13. NOKOV positioning control model

How NOKOV Contributes to the Research

Firstly, we discuss the experimental platform used in this study, which integrates NOKOV motion capture equipment and the Gazebo simulator. Information is transferred through the ROS-Simulink information bridge, allowing users to focus on designing control algorithms and interacting with experimental information during use.

Citation Jun Z, Haoran W, Zhanghuang G, et al. Design and implementation of experimental platform for multi-agent system[C]//2023 9th International Conference on Control Science and Systems Engineering (ICCSSE). IEEE, 2023: 196-201.

Link https://ieeexplore.ieee.org/document/10245091

Design, Modeling and Adaptive Robust Control of a Spatial Symmetric Omni-Directional Aerial Vehicle

Keywords

Unmanned aerial vehicle (UAV), adaptive control, attitude control, sliding mode control

Abstract

The increasing popularity of Unmanned Aerial Vehicles has led to heightened demand for their ability to interact with the environment along with the large flight envelopes. In this letter, we propose a new spatial symmetric fully actuated multirotor (FAM) that is capable of achieving fast, smooth attitude and position motion on the entire special Euclidean group. In addition, this FAM features fixed-tilt bidirectional coaxial rotors compared with the existing literature, enabling large, high-frequency 6D interaction outputs. Furthermore, to address the synchronization control issue of the 6D motion under unknown disturbances, an improved adaptive, time-synchronized, multivariable super-twisting control (ATSMST) is proposed to ensure robustness while still being simple for implementation. Experiments validate its capability of achieving decoupled 6D motion control and precise interaction tracking. Videos of the results are provided to support the experimental findings.

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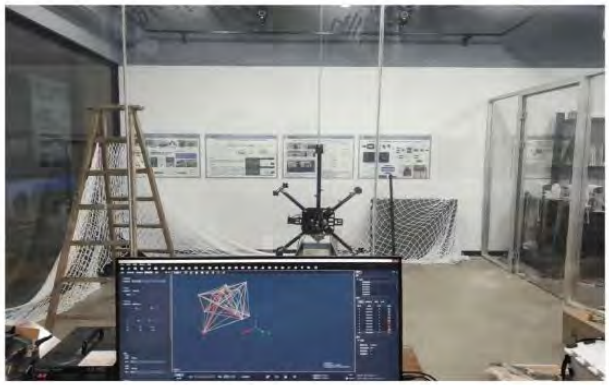

Fig. 11. The indoor optical motion capture system gives the 6D pose.

How NOKOV Contributes to the Research

For the free flight 6D motion test, an indoor optical motion capture system called NOKOV is set up (Fig.11and totally 8cameras). The positional accuracy of the NOKOV is±0.2mmand the raw data is transmitted through USART at 200 Hz, thenmerged with the IMU acceleration data using the Kalman Filter.

Citation Zhu Z, Yu J, Lin Y, et al. Design, modeling and adaptive robust control of a spatial symmetric omni-directional aerial vehicle[J]. IEEE Robotics and Automation Letters, 2024, 9(6): 5958-5965.

Link https://ieeexplore.ieee.org/abstract/document/10517629

Distributed Adaptive Formation Control of Heterogeneous Multi-agent Systems with Unknown System Parameters

Keywords

Distributed adaptive control, multiple unmanned aerial vehicles (UAVs) unmanned ground vehicles (UGVs), formation control

Abstract

In this paper, we consider the leaderless formation control problem for heterogeneous multi-agent systems (MASs) consisting of unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) with unknown system parameters. In order to solve the problem caused by nonidentical subsystem orders, a new distributed reference system is introduced in each agent, in which only the relative positions of the agents are involved. Then, a backstepping-based distributed adaptive control is proposed under directed graph condition. With the proposed control scheme, the boundedness of all the signals in the closed-loop system can be ensured and the positions of heterogeneous MASs can converge to a desired formation. Finally, experimental results are provided to demonstrate the effectiveness of the proposed control scheme.

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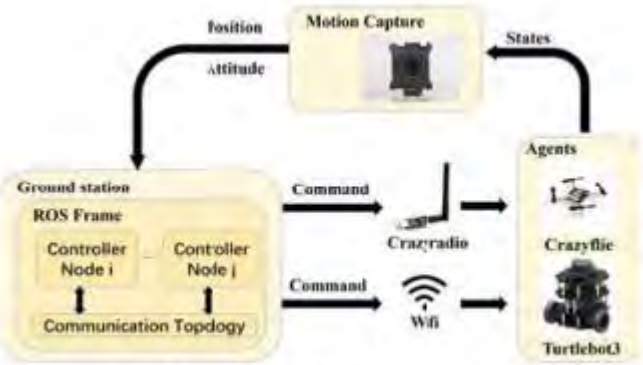

Fig. 1: UAVs and UGVs control framework.

How NOKOV Contributes to the Research

Our real time experiment system framework is illustratedin Fig.1. Crazyflie2.1 UAV and Turtlebot3 UGV are adoptedin the experiment. The NOKOV motion capture is used toobtain the real physical position of the agents. The groundstation is a high performance laptop (Intel Core i5, CPU\@2.2 HZ equipped) with Ubuntu system. The whole softwareframework is programmed with ROS (Robotics Operate Sys-tem). Each controller node simulates an agent's command center and it gets the others' states in ROS communicationnetwork.

Citation Long X, Ze K, Wang W, et al. Distributed Adaptive Formation Control of Heterogeneous Multi-agent Systems with Unknown System Parameters[C]//2024 43rd Chinese Control Conference (CCC). IEEE, 2024: 5931-5936.

Link https://ieeexplore.ieee.org/abstract/document/10662559

Distributed Collision-Free Control of MASs by Combining Reinforcement Learning With Filtered Position Barrier Certificates And Applications

Abstract

This paper presents a novel control framework that combines reinforcement learning (RL) with filtered position barrier certificate (FPBC) for distributed collision-free multi-agent systems (MASs) control. By introducing a filtered position model on the basis of a velocity-controlled double-integral system, the collision avoidance analysis is greatly simplified. The proposed FPBC is designed based on this filtered position model and enables collision-free interaction among agents using a less conservative first-order control barrier function (CBF), thereby eliminating the need for complex high-order CBFs (HOCBFs). The proposed FPBC is used in a Quadratic Program (QP)-based safety filter that enforces collision avoidance on the actions generated by a RL controller. This RL controller only needs to be trained in a single-agent setting and can learn an effective policy through a stability-optimality reward function to reduce computing resource consumption. Furthermore, a deadlock resolution mechanism is proposed to prevent agent stagnation and task failure in large-scale MASs. Extensive simulations and real-world experiments in UGV and UAV environments validate the proposed framework, which demonstrates superior safety and performance compared to conventional HOCBFs.

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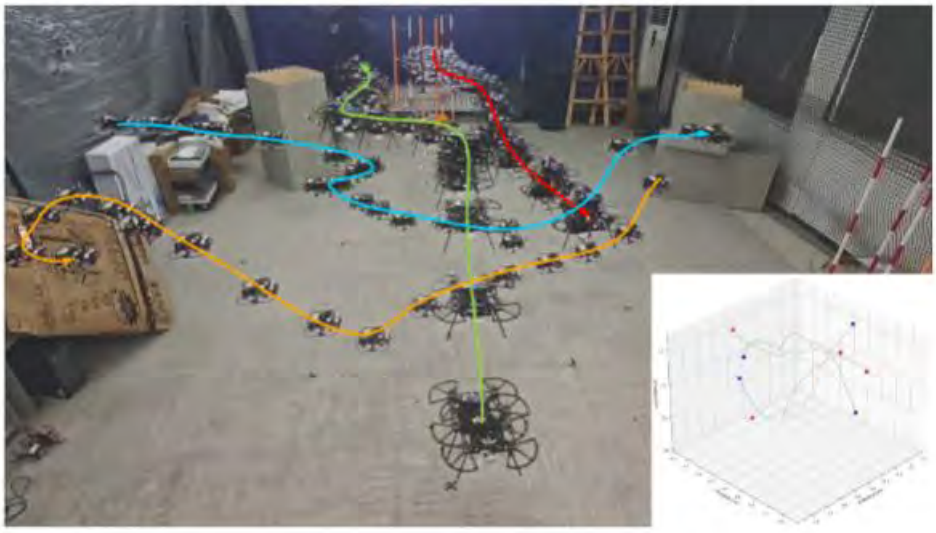

Fig. 13. Experimental results of the 3D crossing task: light trail image showing the UAVs' trajectories with different colors and corresponding 3D position trajectories.

How NOKOV Contributes to the Research

B. Experiments
To validate the effectiveness of the proposed FPBC methodwith our collision-free control framework, we conduct real-world experiments for multi-agent crossing tasks. Due toenvironmental and equipment constraints, these experimentsinvolve 4 UGVs for a 2D environment and 4 UAVs for a 3Denvironment. In the UGV experiment, the time constants in(1) are set asd1=d2=d3=0.05,d4=0.03; for the UAVexperiment, they are set asd1=d2=0.05,d3=d4=0.04. Theminimum safety distancersis set to 0.8m andrd=2m. Theposition and velocity data for each agent are acquired by usinga NOKOV Motion Capture System. The control actions foreach agent are computed and executed on its onboard computerthrough a combination of RL controller and FPBC filter.In the 2D experiment, 4 UGVs are tasked with a crossingmaneuver. As shown in Fig. 9, two different

Citation Qi Q, Lin H, Yang X, et al. Distributed Collision-Free Control of MASs by Combining Reinforcement Learning With Filtered Position Barrier Certificates and Applications[J]. IEEE Transactions on Automation Science and Engineering, 2025, 22: 23849-23860.

Link https://wos.vntr.top/wos/woscc/full-record/WOS:001618903300010

Distributed Fault-Tolerant Consensus Control of Vehicle Platoon Systems With DoS Attacks

Keywords

Distributed fault-tolerant consensus control, decentralized fault-estimation, vehicle platoon systems, aperiodic DoS attacks, actuator and sensor faults

Abstract

Vehicle platoon systems are regarded as autonomous vehicles in the platooning pattern, in which vehicles drive in sequence and maintain the desired inter-vehicle spacing. This paper investigates the platoon control problem of vehicle platoon dynamics under cyber-physical threats through the distributed fault-tolerant consensus control protocol. Complicated sensor and actuator faults in the physical layer and aperiodic denial-of-service (DoS) attacks in the cyber layer are modeled, respectively. Decentralized fault-estimation unknown input observers and event-triggered distributed anti-DoS-attack fault-tolerant consensus controllers are devised in a co-designed framework, thus maintaining not only the tolerance and resilience of platoon consensus errors and estimation errors but also the secure vehicle avoidance spacing by virtue of attack frequency and average dwelling time indicators. Simulations and experiments validate the distributed control algorithm in the pernicious short-cycle and long-cycle DoS attack scenarios.

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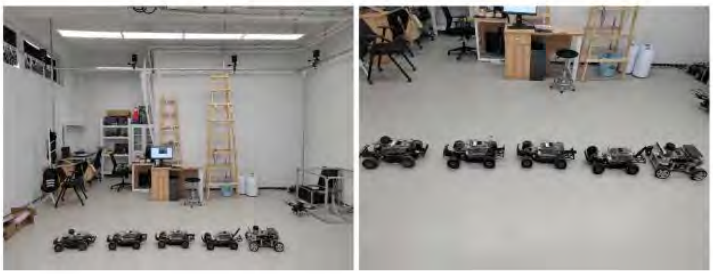

Fig. 6. The experimental testing platform.

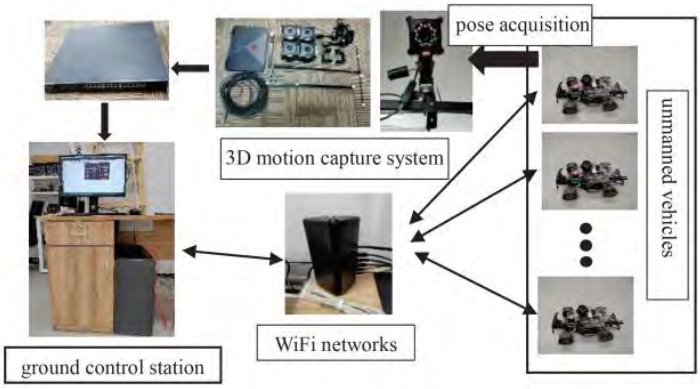

Fig. 7. The major components in the vehicle platoon platform.

How NOKOV Contributes to the Research

The experimental testing platform in our lab (Fig.6) con-sists of four main components: the ground control station, fiveunmanned vehicles, Nokov optical 3D motion capture system,and WiFi-based wireless communication network, as shown inFig.7. The vehicle positions are collected by the motion capturesystem, which envelops the entire capture area of the indoorspace utilizing motion capture cameras arranged within thespace,capturingtheprecisethree-dimensionalspatialpositionofreflective markers placed on the captured subject. This providesreal-time information about the current position and posture ofthe unmanned vehicles.

Citation Liu C, Xia Z, Patton R J. Distributed fault-tolerant consensus control of vehicle platoon systems with DoS attacks[J]. IEEE Transactions on Vehicular Technology, 2024, 73(10): 14438-14449.

Link https://ieeexplore.ieee.org/abstract/document/10540266

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Distributed Formation Shape Control of Identity-Less Robot Swarms

Keywords

Formation maneuver control, formation shape control, identity-less systems, robot swarms

Abstract

Different from most of the formation strategies where robots require unique labels to identify topological neighbors to satisfy the predefined shape constraints, we here study the problem of identity-less distributed shape formation in homogeneous swarms, which is rarely studied in the literature. The absence of identities creates a unique challenge: how to design appropriate target formations and local behaviors that are suitable for identity-less formation shape control. To address this challenge, we propose the following novel results. First, to avoid using unique identities, we propose a dynamic formation description method and solve the formation consensus of robots in a locally distributed manner. Second, to handle identity-less distributed formations, we propose a fully distributed control law for homogeneous swarms based on locally sensed information. While the existing methods are applicable to simple cases where the target formation is stationary, ours can tackle more general maneuvering formations such as translation, rotation, or even shape deformation. Both numerical simulation and flight experiment are presented to verify the effectiveness and robustness of our proposed formation strategy.

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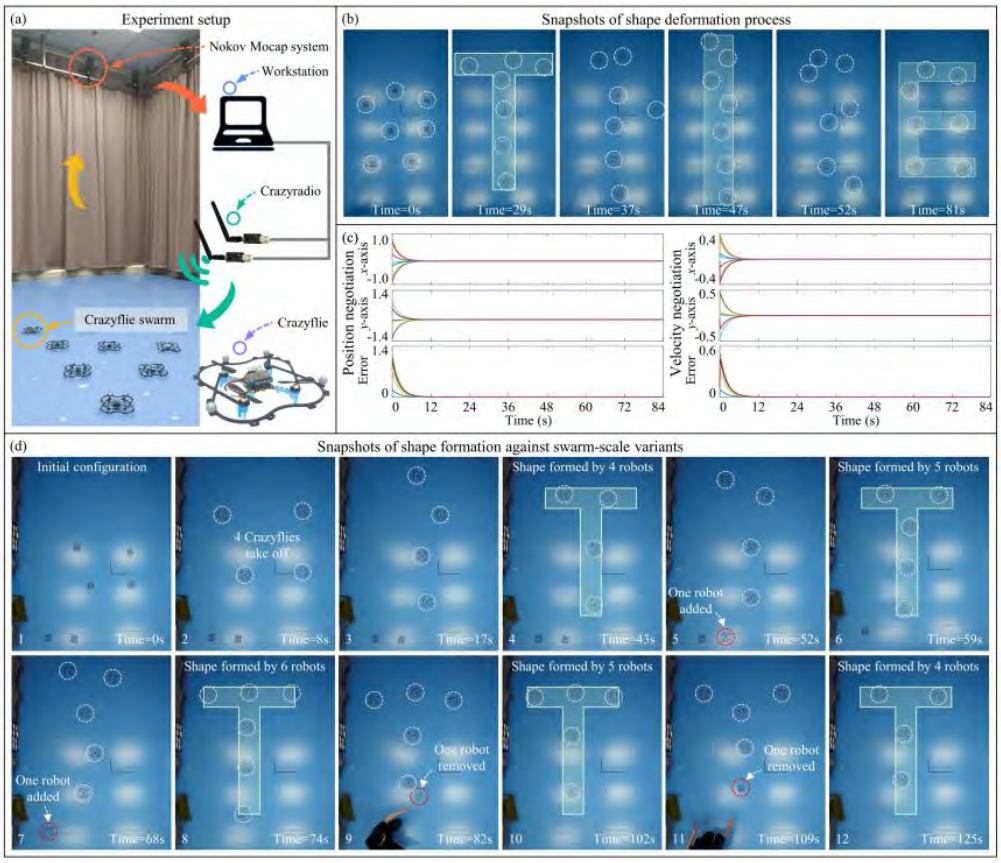

Fig. 4. Experiment results. (a) Experiment and implementation setup. (b) Snapshots of 7 Crazyflies forming three different shapes in a sequence. (c) Position and velocity negotiation in (b). (d) Snapshots of shape formation against group-scale changes. Initially, 4 Crazyflies form the target shape. Then, as 2 Crazyflies are added to and removed from the swarm one by one, the target shape is still formed.

How NOKOV Contributes to the Research

The fourth is a Nokov Mocapsystem used to acquire the position of each robot at a rate of 200Hz. The linear velocity of robot is obtained by taking thederivative and low-pass filtering of its position. Crazychoirprovides an interface for converting acceleration commandsuiinto attitude signals that Crazyflie can receive. The detailedconversion process is shown in the Appendix.

Citation Sun G, Xu Y, Liu K, et al. Distributed Formation Shape Control of Identity-Less Robot Swarms[J]. IEEE Transactions on Industrial Electronics, 2025.

Link https://ieeexplore.ieee.org/abstract/document/10900593

Distributed H∞-Constraint Robust Estimator for Multi-Sensor Networked Hybrid Uncertain Systems

Keywords

Consensus weight strategy, Distributed H1-constraint robust estimator, Multi-sensor networked hybrid uncertain systems, Network-induced uncertainties.

Abstract

Due to the complex communication channel environment, uncertainties, including random measurement delays, missing measurements and uncertain measurement noise variances, often exist in multi-sensor networked hybrid uncertain systems. These uncertainties will lead to poor accuracy and robustness for traditional information fusion methods. Hence, this paper presents a distributed robust estimator based on the H ∞ constraint to solve the mentioned issues in sensor networked systems. The nonlinear pseudomeasurement model is first constructed with Bernoulli distributed random variables to describe the mentioned uncertainties in the communication channels. Then, a sufficient condition with a local optimal upper bound on estimation error covariance is derived rigorously with respect to the robustness definition, which is based on the H ∞ constraint inequality to improve the robustness of state estimation. Furthermore, the proposed estimator is proven to be stable through boundedness analysis for the upper bound matrix. The numerical simulation and the target tracking experiment are finally applied to evaluate the effectiveness of the novel fusion estimator.

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Fig. 4. Experimental platform for target tracking.

How NOKOV Contributes to the Research

To verify the efficiency of the proposed estimator, the experimental platform for multi-sensor target tracking displayed in Fig. 4 is established. As shown in Fig. 4, the devices of the experimental platform include the assembled test car, the NOKOV motion capture system (six Mars 2 cameras), the 24G millimeter-wave radar sensors, PCs, etc. The camera parameters are a detection range of 01m and precision of 0.3mm. Radar parameters are detection range 0.13.5m and precision 50mm. As the tracked target, the test car (system model can refer to [38]) moves in a circular motion under electromagnetic drive, and concurrently, the NOKOV system (submillimeter accuracy) captures the position as the target's real state vector.

Citation Xia J, Gao S, Li G, et al. Distributed H $\infty $-Constraint Robust Estimator for Multi-Sensor Networked Hybrid Uncertain Systems[J]. IEEE Transactions on Network Science and Engineering, 2021, 8(4): 3335-3348.

Link https://ieeexplore.ieee.org/document/9540386

Distributed Heading Synchronization of Multi-Vehicle Systems via Pulse-Based Communication

Keywords

Distributed Heading Synchronization, Multi-Vehicle Systems, Pulse-Based Communication

Abstract

Distributed collective motion coordination has found a variety of applications in both military operations and civilian activities. As a critical component of collective motion coordination, distributed heading synchronization of multi-vehicle systems has received increasing attentions. Most existing approaches usually employ continuous control design followed by discretization based implementation. Such two-stage strategy, however, cannot guarantee the original designed control performance in final implementation since discretization will harm or even destabilize the controller designed in the continuous-time domain. In this paper, motivated by the synchronization of pulse-coupled oscillators, we propose an integrated control and communication approach for distributed heading synchronization of multi-vehicle systems. By leveraging the pulse-based communication, our approach does not need discretization in final implementation, making it feasible to guarantee the original design performance and meanwhile obeying the discrete nature of communication. Furthermore, benefiting from pulse signals containing no information, our proposed approach brings higher degrees of reliability and lower complexity of communication. Numerical simulations and experiments are provided to verify the effectiveness of our approach.

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(a) A picture of Tianbot Mini robot.

(b) A picture of NOKOV system.

Fig. 3: Illustration of experiment platform.

How NOKOV Contributes to the Research

Although Tianbot Mini robot has been embedded with coordination manager,our preliminary results show that the accuracy was not sat-isfactory enough to verify the effectiveness of our approach.Therefore, we leveraged NOKOV system (a motion capturesystem) depicted in Fig. 3 (b) to obtain vehicles' real-timeheading information.

Citation Wang Y, Gao H, Xu J, et al. Distributed Heading Synchronization of Multi-Vehicle Systems via Pulse-Based Communication[C]//2024 43rd Chinese Control Conference (CCC). IEEE, 2024: 6044-6049.

Link https://ieeexplore.ieee.org/abstract/document/10662620/

Disturbance Rejection MPC for Tracking of Wheeled Mobile Robot

Keywords

Disturbance observer (DOB), matched disturbances, model predictive control (MPC), nonholonomic systems

Abstract

This paper develops a disturbance rejection model predictive control (MPC) scheme for tracking nonholonomic vehicle with coupled input constraint and matched disturbances. Two disturbance observers (DOBs) are designed to estimate the unknown disturbances and the disturbances with known harmonic frequencies, respectively. By combining the DOB with MPC, a compound controller is presented. Recursive feasibility of the optimization problem is guaranteed by tightening the terminal region and the input constraint. We show that the system is input-to-state stable if no information about the disturbance is available and can reach an offset-free tracking performance if the harmonic frequencies of the disturbance are known. Finally, simulations and experiments are provided to show the efficiency of the proposed approaches.

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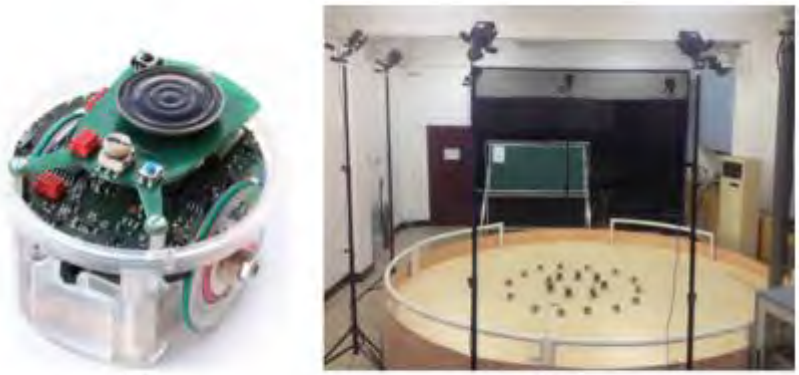

(a) (b)

Fig. 11. Robot and experimental platform. (a) E-puck. (b) Platform.

How NOKOV Contributes to the Research

To demonstrate the effectiveness and the applicability of theproposed scheme, it is desirable to test the scheme on a physicalsystem. The experimental platform is shown inFig. 11, which consists of the E-puck and a Nokov motion capture system(NMCS). The NMCS is equipped with eight cameras to providelocalization and attitude information in real time. Consideringthe computation load of MPC, we compute the optimal controlsignal by MATLAB on a PC and estimate the disturbance onthe local device. Local processing is performed by a dsPICmicrochip on the E-puck that has a digital signal processor coreallowing efficient data processing. The state information and theoptimal control signal are transmitted though a wireless Wi-Finetwork.

Citation Sun Z, Xia Y, Dai L, et al. Disturbance rejection MPC for tracking of wheeled mobile robot[J]. IEEE/ASME Transactions On Mechatronics, 2017, 22(6): 2576-2587.

Link https://ieeexplore.ieee.org/abstract/document/8054727

Dynam-SLAM: An Accurate, Robust Stereo Visual-Inertial SLAM Method in Dynamic Environments

Keywords

Dynamic feature detection, simultaneous localization and mapping (SLAM), state estimation, visual-inertial system

Abstract

Most existing vision-based simultaneous localization and mapping (SLAM) systems and their variants still assume that the observation is absolutely static and cannot work well in dynamic environments. Here, we present the Dynam-SLAM (Dynam), a stereo visual-inertial SLAM system capable of robust, accurate, and continuous work in high dynamic environments. Our approach is devoted to loosely coupling the stereo scene flow with an inertial measurement unit (IMU) for dynamic feature detection and tightly coupling the dynamic and static features with the IMU measurements for nonlinear optimization. First, the scene flow uncertainty caused by measurement noise is modeled to derive the accurate motion likelihood of landmarks. Meanwhile, to cope with highly dynamic environments, we additionally construct the virtual landmarks based on the detected dynamic features. Then, we build a tightly coupled, nonlinear optimization-based SLAM system to estimate the camera state by fusing IMU measurements and feature observations. Finally, we evaluate the proposed dynamic feature detection module (DFM) and the overall SLAM system in various benchmark datasets. Experimental results show that the Dynam is almost unaffected by DFM and performs well in static EuRoC datasets. Dynam outperforms the current state-of-the-art visual and visual-inertial SLAM implementations in terms of accuracy and robustness in self-collected dynamic datasets. The average absolute trajectory error of Dynam in the dynamic benchmark datasets is ~90% lower than that of VINS-Fusion, ~84% lower than that of ORB-SLAM3, and ~88% lower than that of Kimera.

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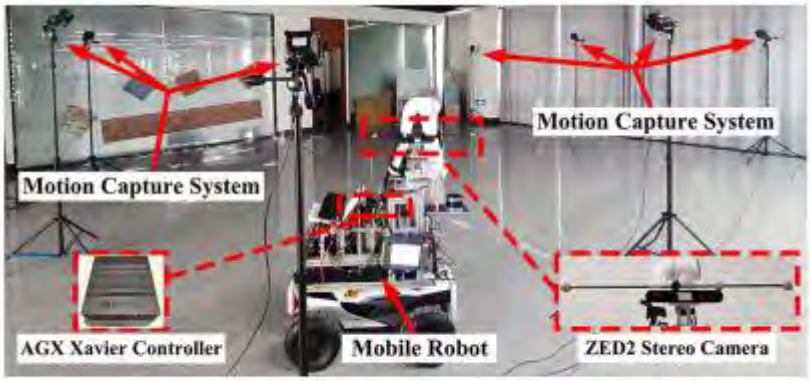

Fig. 10. Hardware settings used in our collection of dynamic datasets.

How NOKOV Contributes to the Research

The room is equipped with aNOKOV3-D optical motion capture system,which provides GT of the camera trajectory with millimetric-level accuracy.
The average velocities, derived from theNOKOVtracking positions and the time intervals of adjacent IMU frames, are considered the GT values.

Citation Yin H, Li S, Tao Y, et al. Dynam-SLAM: An accurate, robust stereo visual-inertial SLAM method in dynamic environments[J]. IEEE Transactions on Robotics, 2022, 39(1): 289-308.

Link https://ieeexplore.ieee.org/abstract/document/9866888

Efficiently Kinematic-Constraint-Coupled State Estimation for Integrated Aerial Platforms in GPS-Denied Environments

Keywords

Aerial systems: applications, localization, multi-robot SLAM

Abstract

Small-scale autonomous aerial vehicles (AAVs) are widely used in various fields. However, their underactuated design limits their ability to perform complex tasks that require physical interaction with environments. The fully-actuated Integrated Aerial Platforms (IAPs), where multiple AAVs are connected to a central platform via passive joints, offer a promising solution. However, achieving accurate state estimation for IAPs in GPS-denied environments remains a significant hurdle. In this letter, we introduce a centralized state estimation framework for IAPs with a fusion of odometry and kinematics, using only onboard cameras and inertial measurement units (IMUs). We develop a forward-kinematic-based formulation to fully leverage localization information from kinematic constraints. An online calibration method for kinematic parameters is proposed to enhance state estimation accuracy with forward kinematics. Additionally, we perform an observability analysis, theoretically proving that these kinematic parameters are fully observable under conditions of fully excited motion. Dataset and real-world experiments on a three-agent IAP prototype confirm that our method improves localization accuracy and reduces drift compared to the baseline.

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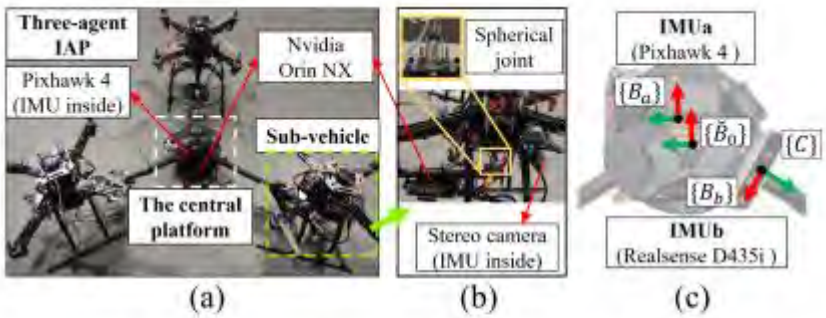

Fig. 3. (a) Prototype of a three-agent IAP where the central platform connects three sub-vehicles via spherical joints. (b) Photograph of the sub-vehicle. (c) A central platform equipped with two IMUs with different locations and orientations.

How NOKOV Contributes to the Research

We evaluate the proposed method using a serial of general 3D handheld trajectories, collected in a 5m×4m area with the NOKOV motion capture system for ground truth. The three-agent IAP prototype shown in Fig. 3 (a) is applied for dataset collection.

Citation Lai G, Yu Y, Sun F, et al. Efficiently Kinematic-Constraint-Coupled State Estimation for Integrated Aerial Platforms in GPS-Denied Environments[J]. IEEE Robotics and Automation Letters, 2025.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001420536700004

Embodied Footprints: A Safety-Guaranteed Collision-Avoidance Model for Numerical Optimization-Based Trajectory Planning

Keywords

Embodied footprint, numerical optimal control, collision avoidance, trajectory planning, motion planning

Abstract

Optimization-based methods are commonly applied in autonomous driving trajectory planners, which transform the continuous-time trajectory planning problem into a finite nonlinear program with constraints imposed at finite collocation points. However, potential violations between adjacent collocation points can occur. To address this issue thoroughly, we propose a safety-guaranteed collision-avoidance model to mitigate collision risks within optimization-based trajectory planners. This model introduces an "embodied footprint", an enlarged representation of the vehicle'nominal footprint. If the embodied footprints do not collide with obstacles at finite collocation points, then the ego vehicle's nominal footprint is guaranteed to be collision-free at any of the infinite moments between adjacent collocation points. According to our theoretical analysis, we define the geometric size of an embodied footprint as a simple function of vehicle velocity and curvature. Particularly, we propose a trajectory optimizer with the embodied footprints that can theoretically set an appropriate number of collocation points prior to the optimization process. We conduct this research to enhance the foundation of optimization-based planners in robotics. Comparative simulations and field tests validate the completeness, solution speed, and solution quality of our proposal.

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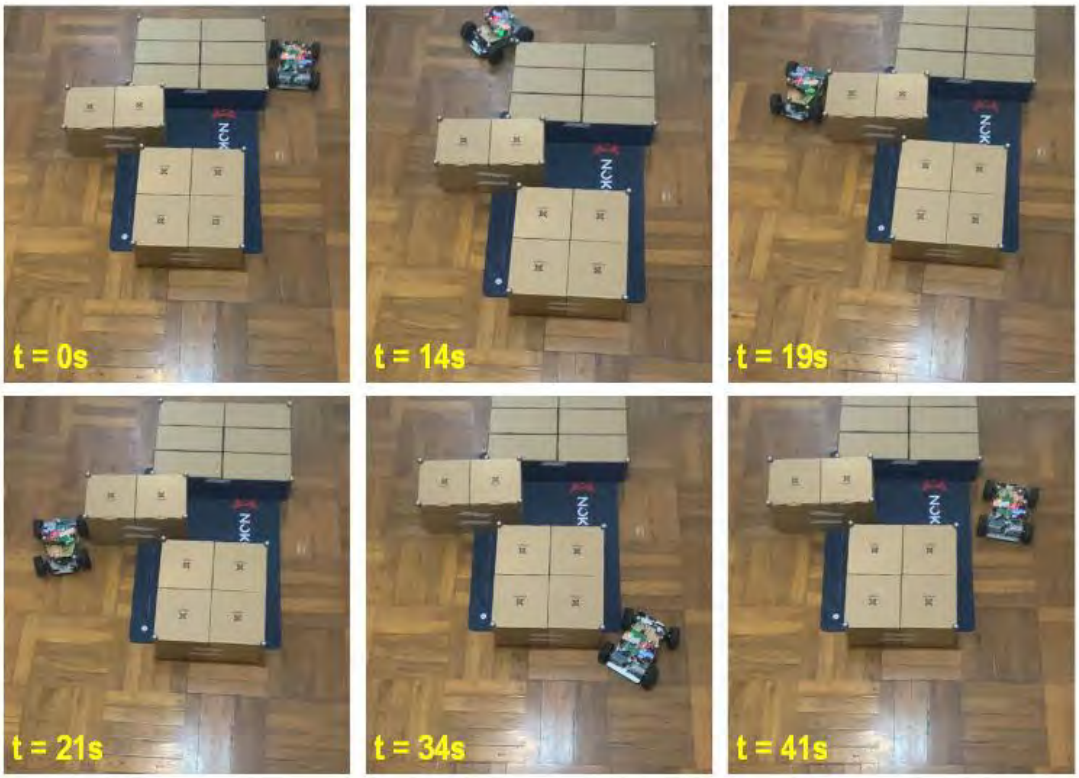

Fig. 15. Snapshots of closed-loop control performance when the ego vehicle is tracking a planned open-loop trajectory, which is derived by a trajectory planner with safe collision-avoidance constraints.

How NOKOV Contributes to the Research

The indoor infrared solution, provided by NOKOV®, was implemented in this study. The infrared sensors from this solution operated at a frequency of 60Hz. The data collected for perception and localization was processed on a desktop computer.

Citation Li B, Zhang Y, Zhang T, et al. Embodied footprints: A safety-guaranteed collision-avoidance model for numerical optimization-based trajectory planning[J]. IEEE Transactions on Intelligent Transportation Systems, 2023, 25(2): 2046-2060.

Link https://ieeexplore.ieee.org/document/10380664?signout=success

Emergent Cooperative Strategies for Pursuit-Evasion in Cluttered Environments: A Knowledge-Enhanced Multi-Agent Deep Reinforcement Learning Approach

Abstract

Deep reinforcement learning (DRL) has recently emerged as a promising tool for tackling pursuit-evasion tasks.However, most existing DRL-based pursuit approaches still relyon individual rewards and struggle with complex scenarios. To address these challenges, we propose a knowledge enhanced DRL approach for multi-agent pursuit-evasion in complex environments. Specifically, the cooperative pursuit problem is modeled as a decentralized partially observable Markov decision process from each pursuers perspective, where the team reward function is elaborately designed to encourage collaborative behavior and enhance team coordination. Then,a novel knowledge enhanced multi-agent twin delayed deep deterministic policy gradient (KE-MATD3) algorithm is presented to efficiently learn the cooperative pursuit policy. By integrating a knowledge enhancement mechanism that extracts effective information from an improved artificial potential field method, the cooperative pursuit policy achieves more robust convergence, mitigating the local optima that typically arise from individual reward-based learning. Finally, extensive numerical simulations and real-world experiments validate the efficiency and superiority of the proposed approach, demonstrating emergent cooperative behaviors among the pursuers.

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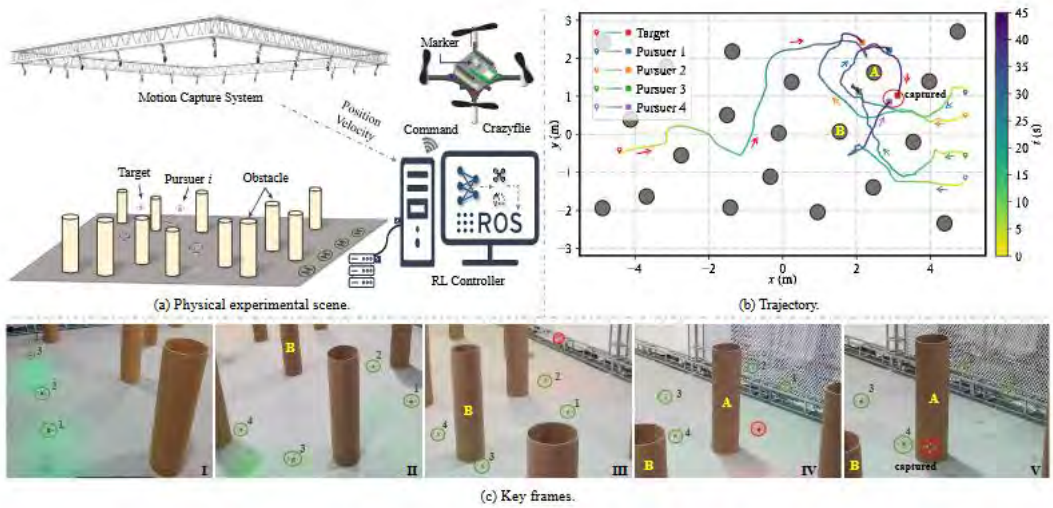

Fig. 5. Physical experimental Results. The flight video is provided in the supplementary material.

How NOKOV Contributes to the Research

As illustrated in Fig.5(a), the real-world system comprises 5 Crazyflie 2.1 quadcopters, a NOKOV motion capture system, 20 cylindrical obstacles, and an onboard computer.

Citation Y. Sun, C. Yan, H. Zhou, X. Xiang and J. Jiang, "Emergent Cooperative Strategies for Pursuit-Evasion in Cluttered Environments: A Knowledge-Enhanced Multi-Agent Deep Reinforcement Learning Approach," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 17138-17145, doi: 10.1109/IROS60139.2025.11246236.

Link https://ieeexplore.ieee.org/document/11246236

Enhancing the terrain adaptability of a multirobot cooperative transportation system via novel connectors and optimized cooperative strategies

Keywords

Multirobot system; Cooperative transportation; Terrain adaptability; Trajectory tracking; Collaborative paradigm; Uneven road

Abstract

Given limited terrain adaptability, most existing multirobot cooperative transportation systems (MRCTSs) mainly work on flat pavements, restricting their outdoor applications. The connectors' finite deformation capability and the control strategies' limitations are primarily responsible for this phenomenon. This study proposes a novel MRCTS based on tracked mobile robots (TMRs) to improve terrain adaptability and expand the application scenarios of MRCTSs. In structure design, we develop a novel 6-degree-of-freedom passive adaptive connector to link multiple TMRs and the transported object (the communal payload). In addition, the connector is set with sensors to measure the position and orientation of the robot with respect to the object for feedback control. In the control strategy, we present a virtual leader–physical follower collaborative paradigm. The leader robot is imaginary to describe the movement of the entire system and manage the follower robots. All the TMRs in the system act as follower robots to transport the object cooperatively. Having divided the whole control structure into the leader robot level and the follower robot level, we convert the motion control of the two kinds of robots to trajectory tracking control problems and propose a novel double closed-loop kinematics control framework. Furthermore, a control law satisfying saturation constraints is derived to ensure transportation stability. An adaptive control algorithm processes the wheelbase uncertainty of the TMR. Finally, we develop a prototype of the TMR-based MRCTS for experiments. In the trajectory tracking experiment, the developed MRCTS with the proposed control scheme can converge to the reference trajectory in the presence of initial tracking errors in a finite time. In the outdoor experiment, the proposed MRCTS consisting of four TMRs can successfully transport a payload weighing 60 kg on an uneven road with the single TMR's maximum load limited to 15 kg. The experimental results demonstrate the effectiveness of the structural design and control strategies of the TMR-based MRCTS.

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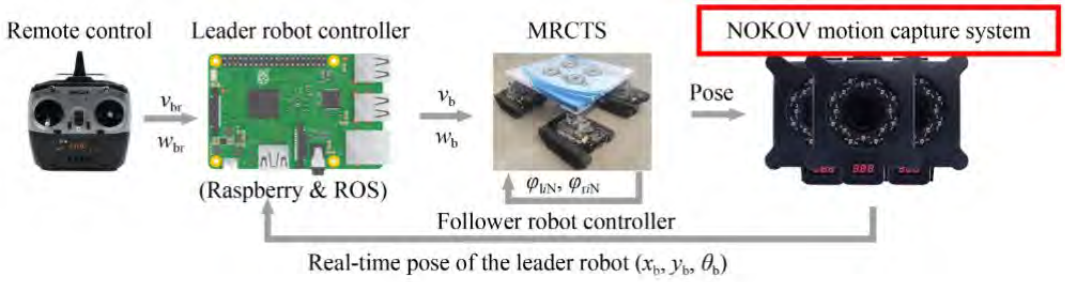

How NOKOV Contributes to the Research

For feedback control, the NOKOV motion capture system is adopted to collect the leader robot's real-time pose information. We apply eight cameras to capture the leader robot's position and orientation information within a 4.5 m × 4.5 m venue.

Citation Liu Q, Gong Z, Nie Z, et al. Enhancing the terrain adaptability of a multirobot cooperative transportation system via novel connectors and optimized cooperative strategies[J]. Frontiers of Mechanical Engineering, 2023, 18(3): 38.

Link https://link.springer.com/article/10.1007/s11465-023-0754-2

Environmental-Adaptive Trajectory Prediction of Multi-Object for UAV Networks with RGBD Camera

Keywords

Features association, multi-object tracking, environmental-adaptive, trajectory prediction, unmanned aerial vehicle (UAV) networks

Abstract

In unknown environment, the most existing unmanned aerial vehicles (UAV) networks usually supports single-object trajectory prediction due to the limitation of computing resources and energy. However, multi-object trajectory prediction and environmental-adaptive ability of the UAV networks are very important in the actual scenario. In this paper, an environmental-adaptive trajectory prediction approach is proposed to improve the ability of multi-object tracking and trajectory prediction in UAV networks. The approach consist of object detection, tracking and trajectory prediction. Firstly, the object detection is performed on RGB images and combined with depth images to obtain object three dimensional (3D) position. Secondly, a multi-object tracking method based on the association of positional and shape features is constructed to obtain the real-time state of the objects. Thirdly, an environmental-adaptive trajectory prediction method is carried out by dynamically adjusting the object tracking frequency and trajectory prediction time step. Finally, the results show that the proposed approach can perform accurate multi-object trajectory prediction and adjust the calculation parameters according to the change of the environment.

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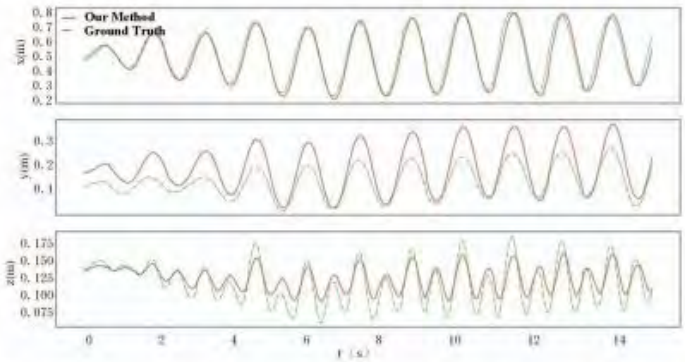

Fig. 5. The comparison of the estimated states of the ball by our method and ground truth obtained by NOKOV.

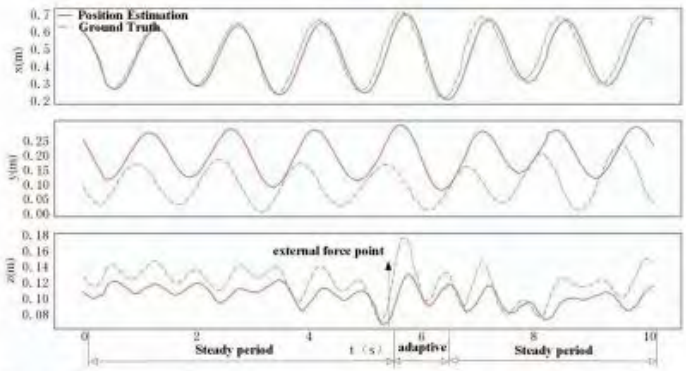

Fig. 6. The comparison of the estimated states of the ball by our method in the presence of external interference and ground truth obtained by NOKOV.

How NOKOV Contributes to the Research

*We use Yolo-Fastestv2 algorithm, whichis a light and fast object detection algorithm. The input imagesize is set at672*672pixels, and the dynamic objects isreplaced by 7cm balls. The overview of our UAV system isshown in Fig. 4. In this paper, in order to verify the accuracyand robustness of our system, the NOKOV motion capturesystem is used to obtain high-precision object information.The measurement accuracy of the system is 0.019mm.*

Citation Zhong Y, Li X, Wu P, et al. Environmental-Adaptive Trajectory Prediction of Multi-Object for UAV Networks with RGBD Camera[C]//2023 IEEE International Conferences on Internet of Things (iThings) and IEEE Green Computing & Communications (GreenCom) and IEEE Cyber, Physical & Social Computing (CPSCom) and IEEE Smart Data (SmartData) and IEEE Congress on Cybermatics (Cybermatics). IEEE, 2023: 347-353.

Link https://ieeexplore.ieee.org/abstract/document/10501891

ESVO2: Direct Visual-Inertial OdometryWith Stereo Event Camera

Keywords

Event-based cameras, simultaneous localization and mapping, visual odometry, visual-inertial fusion

Abstract

Event-based visual odometry is a specific branch of visual simultaneous localization and mapping (SLAM) techniques, which aims at solving tracking and mapping subproblems (typically in parallel), by exploiting the special working principles of neuromorphic (i.e., event-based) cameras. Due to the motion-dependent nature of event data, explicit data association (i.e., feature matching) under large-baseline viewpoint changes is difficult to establish, making direct methods a more rational choice. However, state-of-the-art direct methods are limited by the high computational complexity of the mapping subproblem and the degeneracy of camera pose tracking in certain degrees of freedom (DoF) in rotation. In this article, we tackle these issues by building an event-based stereo visual-inertial odometry system, which is built upon a direct pipeline known as event-based stereo visual odometry (ESVO). Specifically, to speed up the mapping operation, we propose an efficient strategy for sampling contour points according to the local dynamics of events. The mapping performance is also improved in terms of structure completeness and local smoothness by merging the temporal stereo and static stereo results. To circumvent the degeneracy of camera pose tracking in recovering the pitch and yaw components of general 6-DoF motion, we introduce IMU measurements as motion priors via preintegration. To this end, a compact back-end is proposed for continuously updating the IMU bias and predicting the linear velocity, enabling an accurate motion prediction for camera pose tracking. The resulting system scales well with modern high-resolution event cameras and leads to better global positioning accuracy in large-scale outdoor environments. Extensive evaluations on five publicly available datasets featuring different resolutions and scenarios justify the superior performance of the proposed system against five state-of-the-art methods. Compared to ESVO, our new pipeline significantly reduces the camera pose tracking error by 40%–80% and 20%–80% in terms of absolute trajectory error and relative pose error, respectively; at the same time, the mapping efficiency is improved by a factor of five. We release our pipeline as an open-source software for future research in this field.

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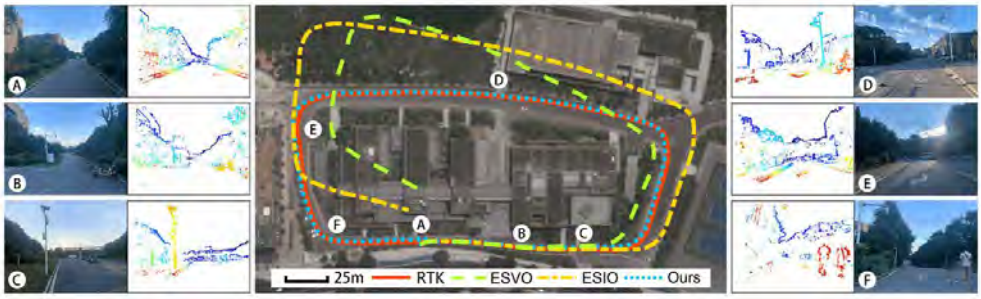

Fig. 1. Proposed event-based stereo visual-inertial odometry system (ESVO2) operates in real time on large-scale VGA-resolution sequences like *hmu_campus* utilizing a standard CPU. Middle: The ground truth of the trajectory is provided by real-time kinematic (RTK) positioning (red) and is aligned with Google Maps. Our method achieves the best performance in terms of global trajectory consistency, while significant drift is witnessed in the results of ESVO [1] (green) and ESIO [2] (yellow). Left and right: Depth maps reconstructed by our system and corresponding scene images (for visualization purposes only). The locations where visual measurements are captured are associated to the map using letters with a circle around them.

How NOKOV Contributes to the Research

Besides, we observe that ESVO's tracking module sometimes cannot fully recover the yaw and pitch components in general 6-DoF motion, which degrades the accuracy of the recovered trajectory. To resolve these issues, we recently proposed an IMU-aided version of ESVO. By employing an efficient strategy for sampling contour points, it scales better with modern event cameras of VGA resolution.

Citation Niu J, Zhong S, Lu X, et al. Esvo2: Direct visual-inertial odometry with stereo event cameras[J]. IEEE Transactions on Robotics, 2025.

Link https://ieeexplore.ieee.org/abstract/document/10912788

Event-based Visual-Inertial State Estimation for High-Speed Maneuvers

Abstract

Neuromorphic event-based cameras are bio-inspired visual sensors with asynchronous pixels and extremely high temporal resolution. Such favorable properties make them an excellent choice for solving state estimation tasks under high-speed maneuvers. However, failures of camera pose tracking are frequently witnessed in state-of-the-art event-based visual odometry systems when the local map cannot be updated timely or feature matching is unreliable. One of the biggest roadblocks in this field is the absence of efficient and robust methods for data association without imposing any assumptions on the environment. This problem seems, however, unlikely to be addressed as in standard vision because of the motion-dependent nature of event data. To address this, we propose a map-free design for event-based visual-inertial state estimation in this paper. Instead of estimating camera position, we find that recovering the instantaneous linear velocity aligns better with event cameras' differential working principle. The proposed system uses raw data from a stereo event camera and an inertial measurement unit (IMU) as input, and adopts a dual-end architecture. The front-end preprocesses raw events and executes the computation of normal flow and depth information. To handle the temporally non-equispaced event data and establish association with temporally non-aligned IMU's measurements, the back-end employs a continuous-time formulation and a sliding-window scheme that can progressively estimate the linear velocity and IMU's bias. Experiments on synthetic and real data show our method achieves low-latency, metric-scale velocity estimation. To the best of our knowledge, this is the first real-time, purely event-based visual-inertial state estimator for high-speed maneuvers, requiring only sufficient textures and imposing no additional constraints on either the environment or motion pattern.

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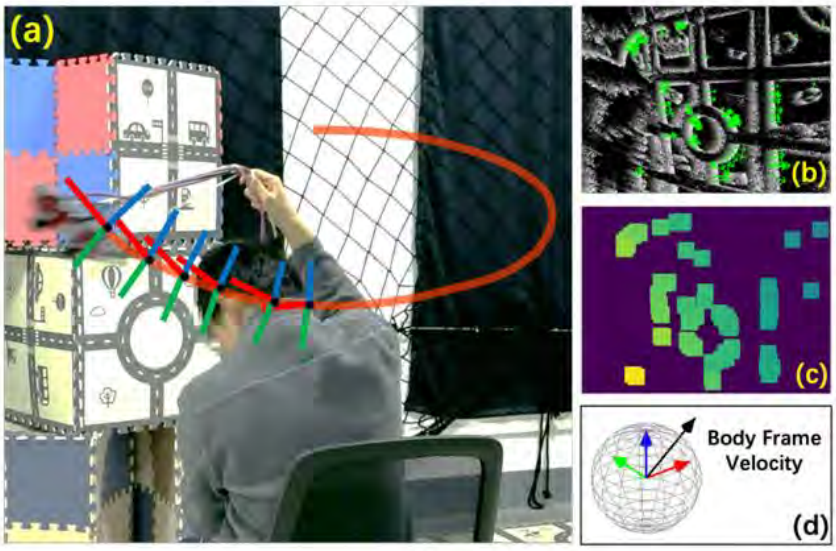

Fig. 1: The proposed system takes as input the event data from a stereo event-based camera and inertial measurements from an IMU, and recovers the instantaneous linear velocity of the sensor suite. (a) High-speed motion induced by horizontally spinning the tethered sensor suite. (b) Sparse and asynchronous normal-flow estimates from event data. (c) Sparse depth estimates at the corresponding origins of the normal-flow vectors. (d) Illustration of the resulting instantaneous linear velocity in the sensor's body frame.

How NOKOV Contributes to the Research

A pair of DAVIS-346 cameras are used in data collection. All the real data are collected in a room equipped with a motion capture (MoCap) system. By attaching several visual markers to the stereo rig and the carrier, the MoCap system can report 6-DoF poses (RWMRWM and tWMtWM) of the marker coordinate system up to 200 Hz with sub-millimeter accuracy.

Citation Lu X, Zhou Y, Mai J, et al. Event-Based Visual-Inertial State Estimation for High-Speed Maneuvers[J]. IEEE Transactions on Robotics, 2025.

Link https://ieeexplore.ieee.org/abstract/document/11059886

EventTracker: 3D Localization and Tracking of High-Speed Object with Event and Depth Fusion

Keywords

Perception, Event Camera, Optimization, Object Tracking

Abstract

Accurately localizing high-speed dynamic objects in 3D space with low latency is crucial for various robotic applications. Current methods face challenges due to extended exposure times and limited sensor resolution, hindering precise object detection and localization. Event cameras, known for their high temporal resolution and asynchronous nature, offer a promising solution. To leverage the potential of the event camera, we propose EventTracker, a novel framework that integrates event and depth measurements for precise and low-latency 3D localization and tracking of the high-speed dynamic object. EventTracker incorporates a collaborative object detection and tracking algorithm optimized for both event and depth data, overcoming detection and registration challenges. Additionally, a graph-instructed optimization algorithm enhances accuracy by fusing heterogeneous sensor data effectively. Experimental evaluation in dynamic environments demonstrates significant improvements in localization performance compared to baseline methods.

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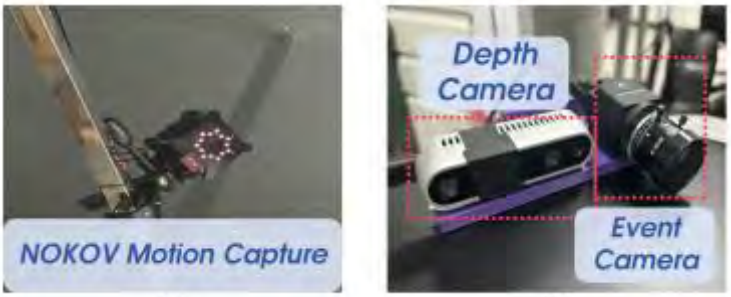

(a) (b)

How NOKOV Contributes to the Research

To validate our proposed approach, we conducted experiments in a laboratory setting. We utilized a Intel Real sense D435idepth camera and a Prophesee EVK4 HD event camera for data collection (Fig.6a). Meanwhile, we employed a motion capture system with fourteen NOKOV cameras (Fig.6b) to collect ground truth at the frequency of 240hz. In our experiment, we aimed to validate our 3D tracking system by estimating the position and trajectory of dynamically moving objects such as balls and drones. These objects exhibited different and random movement patterns, providing a robust test for our tracking algorithm.

Citation Luo X, Wang H, Ruan C, et al. Eventtracker: 3d localization and tracking of high-speed object with event and depth fusion[C]//Proceedings of the 30th Annual International Conference on Mobile Computing and Networking. 2024: 1974-1979.

Link https://dl.acm.org/doi/10.1145/3636534.3694721

Event-Triggered Control for Inter-Vehicle Communications of Cyber-Physical Transportation Systems

Keywords

Cyber-Physical Transportation Systems, reliability, event-triggered broadcast control

Abstract

In Cyber-Physical Transportation Systems (CPTSs), inter-vehicle communication is a basis of traffic safety and vehicle applications. Vehicles need to transmit motion data with each other via wireless networks. Despite many strategies that make the vehicle network more reliable and efficient under the noise, the separate design of estimation and communication makes them incapable of ensuring state received from multiple vehicles around reliability. To address the gap, this paper proposes an event-triggered broadcast control strategy that fuses communication scheduling with estimators. The estimator is designed to estimate the information transmitted by the strategy and the event-triggered condition is designed based on estimation states. To verify the performance of the estimator and the tracking accuracy of the broadcast strategy, an autonomous driving simulation platform is built. The communication rates of our strategy in the traffic flow are evaluated by SUMO and NS3. The experiment result shows that the strategy can dynamically adjust the event-triggered conditions according to the accuracy of the vehicle estimator and the network transmission rate improve significantly.

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Fig. 5: Layout of the platform.

How NOKOV Contributes to the Research

In Cyber-Physical Transportation Systems (CPTSs), inter-vehicle communication is a basis of traffic safety and vehicle applications. Vehicles need to transmit motion data with each other via wireless networks. Despite many strategies that make the vehicle network more reliable and efficient under the noise, the separate design of estimation and communication makes them incapable of ensuring state received from multiple vehicles around reliability. To address the gap, this paper proposes an event-triggered broadcast control strategy that fuses communication scheduling with estimators. The estimator is designed to estimate the information transmitted by the strategy and the event-triggered condition is designed based on estimation states. To verify the performance of the estimator and the tracking accuracy of the broadcast strategy, an autonomous driving simulation platform is built. The communication rates of our strategy in the traffic flow are

Citation Jiang F, Liu X D, Zhang L. Event-triggered control for inter-vehicle communications of cyber-physical transportation systems[C]//2021 40th Chinese Control Conference (CCC). IEEE, 2021: 4709-4714.

Link https://ieeexplore.ieee.org/abstract/document/9550400

Event-triggered MCC-CKF for robust state estimation in complex environments with non-Gaussian noise and communication constraints

Keywords

Non-Gaussian noises, Cubature Kalman filter, Maximum correntropy, Event-triggered, Packet dropout

Abstract

Estimating the target process state is crucial in fields such as robotic vision, navigation, target tracking, and autonomous vehicles. While existing methods excel under precise measurements and Gaussian noise, they struggle in practical scenarios due to several challenges: (1) non-Gaussian noise in both process and measurement, (2) constrained communication resources, and (3) measurement outliers that affect estimation accuracy. These challenges collectively affect estimation performance, necessitating a holistic framework to address their coupled effects. To address these issues, we propose both local and distributed filtering algorithms based on a modified event-triggered cubature Kalman filter (CKF) strategy. Our approach formulates a modified cost function using maximum correntropy criterion, enhancing state estimates and nonlinear measurement functions. We also refine the event-triggered strategy by incorporating measurement innovation and introduce an adaptive weighted fusion rule based on Mahalanobis distance. Equipped them all, the proposed algorithm reduces data communication rates by 27% (event-triggered threshold $\delta = 0.15$) and improves distributed fusion accuracy by about 2.2 times compared with existing methods. Comprehensive numerical simulations validate our approach, and a real target tracking experiment demonstrates that, despite using low-accuracy ($\approx$ 5cm) and high-latency ($\geq$ 60cm)) radar, we achieve a remarkable state estimation accuracy of $\approx$ 2.5 cm. The proposed method holds promise for navigation, robotic awareness and sensing.

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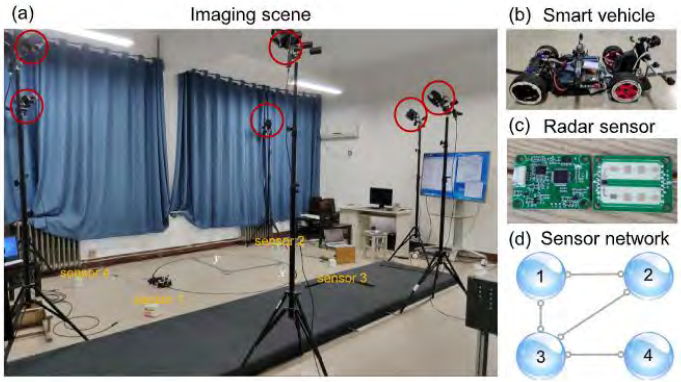

Fig. 7. Experimental scenario of target tracking. (a) Experimental setup. (b) Smart vehicle. (c) Radar sensor. (d) Network topology of four radar sensors.

How NOKOV Contributes to the Research

We verify the algorithm through a real target tracking experiment(Fig.7). The setup includes a Nokov motion capture system with six Mars 2 cameras, a 28 cm x 18 cm vehicle, and four 24 GHz radarsensors arranged in trapezoidal configuration. The vehicle moves ina circular path (95 cm radius)under electromagnetic induction. TheNokov system provides ground truth data (red circles in Fig. 8(a),(cg)), while the four radar sensors form a multi-sensor network (topologyshown in Fig. 7(d)). Technical specifications are listed in Table 4.

Citation Li G, Gao Z, Li W, et al. Event-triggered MCC-CKF for robust state estimation in complex environments with non-Gaussian noise and communication constraints[J]. Measurement, 2025: 117939.

Link https://www.sciencedirect.com/science/article/abs/pii/S0263224125012989

Evolution of UAV landing structures in the bistable space of Kresling origami structures

Keywords

Origami structure, graph method, evolutionary design, unmanned aerial vehicle

Abstract

Landing gear plays an important role in enabling unmanned aerial vehicles to engage in complex missions and protect expensive airborne sensors. Most existing landing gears are designed to satisfy only specific maneuvers in predefined scenarios. Although effective in predefined scenarios, these landing gears cannot guarantee the adaptiveness in multiple scenarios. A promising solution is to build a model automatically generated based on the actual requirements, so that the expected model structure can be obtained through a constraint generation process. However, translating the actual requirements into reasonable design constraints is complex. For this purpose, we propose a landing structure design process in the bistable space of the Kresling tube. Furthermore, we use a combination of graph search and controller to optimize the landing structure. We validate the bistatic and graph search combined design structure in a realistic environment and test the mechanisms flexibility and assisted landing capability. Experiments show that the structure combining spatial bistability with a graph search approach can safely and successfully land a quadrotor under various conditions while enhancing the UAV's shock absorption during landing.

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TABLE III
EXPERIMENTAL EQUIPMENT DETAILS

Drone wheelbase	250(mm)
Onboard computer	Intel NUC
Analysis Tool	NOKOV optical motion capture system

How NOKOV Contributes to the Research

This section details the experimental procedure, experimental setup, and experimental results to validate the bistable design for the verification landing. To reduce the influence of the experimental subjects on the results, we adjusted the weight of all three sets of equipment to 1.44 (kg), where the weight of the bistable design and the non-bistable design structure is the same; both are 383 (g). Additional detailed experimental equipment is shown in Table III. Fig. 9. shows the velocity and acceleration changes of different landing systems within 2.5 seconds after contacting the ground in the indoor experiment, and Fig. 10. shows the testing process of varying landing systems in outdoor scenarios. The experimental results show that the bistable landing structure performs better in the landing process in both indoor and outdoor scenarios

Citation Li H, Du Z, Luo C. Evolution of UAV landing structures in the bistable space of Kresling origami structures[J]. IEEE Robotics and Automation Letters, 2023, 8(4): 2070-2077.

Link

https://ieeexplore.ieee.org/search/searchresult.jsp?newsearch=true&queryText=Evolution%20of%20UAV%20landing%20structures%20in%20the%20bistable%20space%20of%20Kresling%20origami%20structures

Exploiting Hierarchical Symmetry in Multi-Agent Reinforcement Learning

Abstract

Achieving high sample efficiency is a critical research area in reinforcement learning. This becomes extremely difficult in multi-agent reinforcement learning (MARL), as the capacity of the joint state and action space grows exponentially with the number of agents. The reliance of MARL solely on exploration and trial-and-error, without incorporating prior knowledge, exacerbates the issue of low sample efficiency. Currently, introducing symmetry into MARL is an effective approach to address this issue. Yet the concept of hierarchical symmetry, which maintains symmetry across different levels of a multi-agent system (MAS), has not been explored in existing methods. This paper focuses on multi-agent cooperative tasks and proposes a method incorporating hierarchical symmetry, termed the Hierarchical Equivariant Policy Network (HEPN) which is O(n)-equivariant. Specifically, HEPN utilizes clustering to perform hierarchical information extraction in MAS, and employs graph neural networks to model agent interactions. We conducted extensive experiments across various multi-agent tasks. The results indicate that our method achieves faster convergence speeds and higher convergence rewards compared to baseline algorithms. Additionally, we have deployed our algorithm in a physical multi-robot system, confirming its effectiveness in real-world environments. Supplementary materials are available at unmapped: uri https://yongkai-tian.github.io/HEPN/.

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(a) Rendezvous (b) Pursuit (c) Resource Collection

Figure 6. Demonstration of the physics environments across three tasks.

How NOKOV Contributes to the Research

In this section, we evaluate the performance of algorithms througha Sim2Real approach. We have deployed our trained models in areal-world setting to assess their effectiveness across all three tasks.Specifically, Limo robots are employed as the task agents, which arecontrolled via the Robot Operating System (ROS) [13] and supple-mented with a NOKOV motion capture system to get real-time envi-ronment states. Figure 6 provides a schematic of the actual applica-tion scenario.

Citation Tian, Yongkai, et al. "Exploiting Hierarchical Symmetry in Multi-Agent Reinforcement Learning." ECAI 2024. IOS Press, 2024. 2202-2209.

Link https://ebooks.iospress.nl/doi/10.3233/FAIA240741

Exploring the criticality hypothesis using programmable swarm robots with Vicsek-like interactions

Keywords

criticality, collective response, swarm robots, self-organization, alignment, ordered – disordered motion transition

Abstract

A widely mentioned but not experimentally confirmed view (known as the ' criticality hypothesis ') argues that biological swarm systems gain optimal responsiveness to perturbations and information processing capabilities by operating near the critical state where an ordered-to-disordered state transition occurs. However, various factors can induce the ordered–disordered transition, and the explicit relationship between these factors and the criticality is still unclear. Here, we present an experimental validation for the criticality hypothesis by employing real programmable swarm-robotic systems (up to 50 robots) governed by Vicsek-like interactions, subject to time-varying stimulus-response and hazard avoidance. We find that (i) not all ordered–disordered motion transitions correspond to the functional advantages for groups; (ii) collective response of groups is maximized near the critical state induced by alignment weight or scale rather than noise and other non-alignment factors; and (iii) those non-alignment factors act to highlight the functional advantages of alignment-induced criticality. These results suggest that the adjustability of velocity or directional coupling between individuals plays an essential role in the acquisition of maximizing collective response by criticality. Our results contribute to understanding the adjustment strategies of animal interactions from a perspective of criticality and provide insights into the design and control of swarm robotics.

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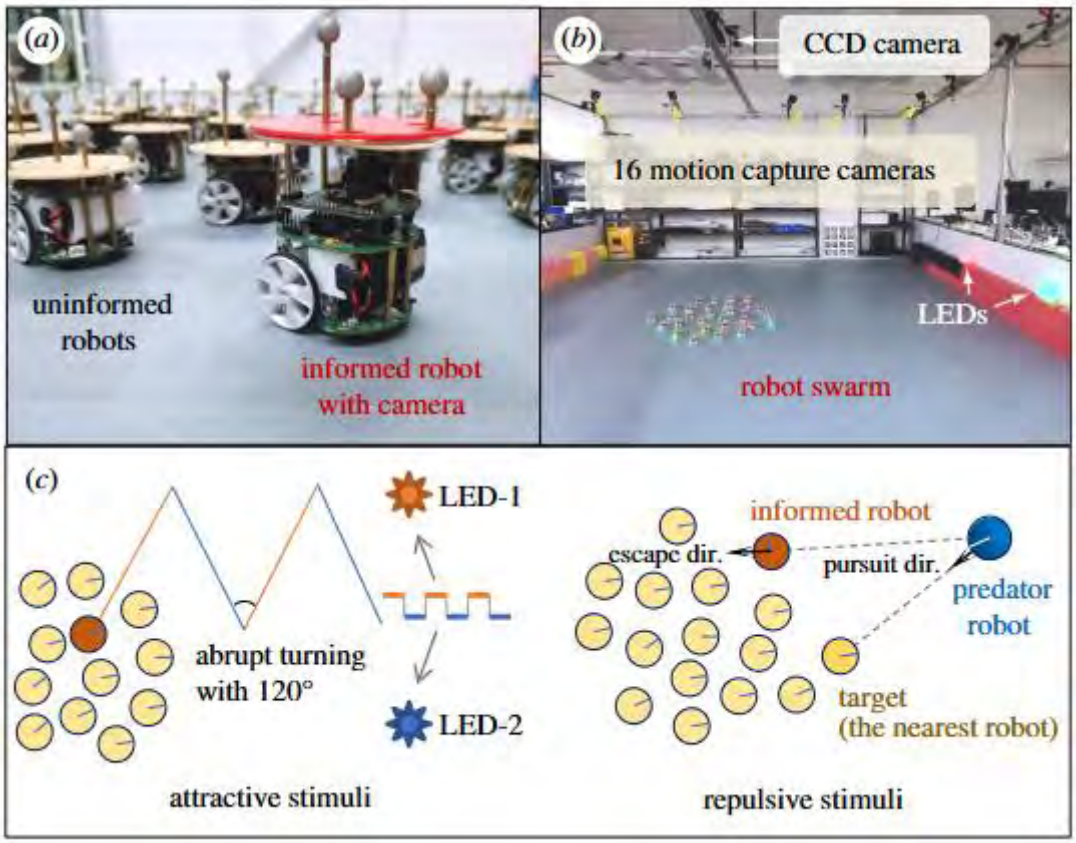

How NOKOV Contributes to the Research

Our experiments are conducted in an approximately 6.0 m × 6.0 m arena with boundary, see figure 1b, in which a CCD camera (Basler a2A4504-18ucPRO with Kowa LM6FC24M lens) with top-down view is used to record experimental videos. We employ a motion capture system (NOKOV) to track the location and orientation of each robot, from which the robot's real-time linear speed and angular speed are derived by differential calculation.

Citation Lei Xiaokang, Xiang Yalun, Duan Mengyuan and Peng Xingguang 2023Exploring the criticality hypothesis using programmable swarm robots with Vicsek-like interactionsJ. R. Soc. Interface.2020230176.https://doi.org/10.1098/rsif.2023.0176

Link https://royalsocietypublishing.org/doi/10.1098/rsif.2023.0176

Exponential Tracking Control With Guaranteed Performance for Strict-Feedback Systems Under Deferred Full-State Asymmetric Constraints

Keywords

Exponential tracking control, prescribed performance, strict-feedback systems, deferred asymmetric constraints

Abstract

This work provides an exponential tracking control solution for a class of nonlinear systems characterized by unmatched, non-vanishing uncertainties and deferred full-state constraints. The presence of both non-vanishing and unmatched uncertainties complicates the task of achieving exponential tracking rather than regulation, particularly in scenarios involving deferred full-state asymmetric constraints alongside steady-state and transient performance requirements. To address these challenges, several key techniques are employed. Firstly, a time-varying feedback gain technique is utilized to ensure exponential tracking of the strict-feedback system. Secondly, we develop an asymmetric constraint mapping function that integrates the system state, tracking error, a finite-time adjustment function (AF), and an exponential AF to tackle performance issues without violating the deferred full-state asymmetric constraints, even when the initial conditions are unknown. Thirdly, an important lemma is derived to guarantee the boundedness of virtual controller derivatives, even as the exponential AF approaches infinity. Additionally, all signals in the closed-loop system are ultimately uniformly bounded. The effectiveness of the proposed scheme is validated through two examples. Note to Practitioners—In most existing studies on constrained systems, the results primarily focus on ensuring ultimately uniformly bounded behavior or asymptotic stability, with exponential tracking being rarely achieved. This paper aims to address this gap by proposing a robust adaptive control solution for uncertain strict-feedback systems under deferred full-state asymmetric constraints, achieving state-of-the-art exponential tracking performance. Furthermore, the steady-state and transient performance can be tailored by selecting an appropriate exponential adjustment function. Notably, the proposed approach ensures that system states remain within the asymmetric constraint boundaries after a finite time T, even with unknown initial conditions. This scenario is particularly relevant to physical systems transitioning from an unconstrained to a constrained state. The feasibility of the

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proposed method is demonstrated through a simulation example and a physical experiment on the Turtlebot 3-Burger robot. Future work will explore extending this approach to multi-agent systems for tasks such as formation control and consensus achievement.

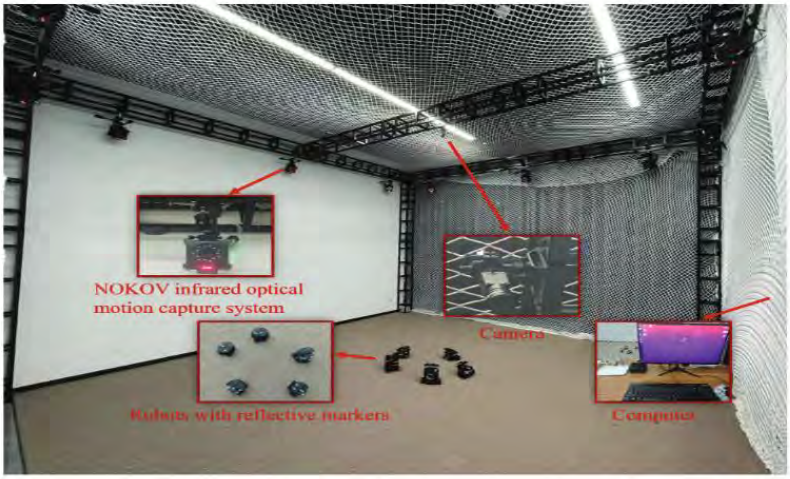

Fig. 4. The experimental setup.

How NOKOV Contributes to the Research

To validate our control scheme in real-worldscenarios, we conduct the experiment on the TurtleBot 3mobile robot. The system, powered by an NUC11TNK-i7processor with Ubuntu 18.04 and the Robot Operating System(ROS), processed perception data from the NOKOV infraredoptical motion capture system. The motion capture systemcan provide accurate position and orientation information. Thecontrol signals are wirelessly broadcasted to the robot via aZigbee module. The robot is modeled as a first-order systembased on the real dynamics model \[46]. The experimentalsetup, shown in Fig. 4, includes the hardware configurationrequired for this test.

Citation Dai Y, Wang Y, Shao Z, et al. Exponential tracking control with guaranteed performance for strict-feedback systems under deferred full-state asymmetric constraints[J]. IEEE Transactions on Automation Science and Engineering, 2025.

Link https://ieeexplore.ieee.org/document/10993457

FACT: Fast and Active Coordinate Initialization for Vision-Based Drone Swarms

Keywords

Aerial systems, perception and autonomy, swarm robotics, vision-based navigation

Abstract

Coordinate initialization is the first step in accomplishing collaborative tasks within robot swarms, determining the quality of tasks. However, fast and robust coordinate initialization in vision-based drone swarms remains elusive. To this end, our letter proposes a complete system for initial relative pose estimation, including both relative state estimation and active planning. Particularly, our work fuses onboard visual-inertial odometry with vision-based observations generating bearing and range measurements, which are anonymous, partially mutual, and noisy. It is the first method based on convex optimization to initialize coordinates with vision-based observations. Additionally, we designed a lightweight module to actively control the movement of robots for observation acquisition and collision avoidance. With only stereo cameras and inertial measurement units as sensors, we validate the practicability of our system in simulations and real-world areas with obstacles and without signals from the Global Navigation Satellite System. Compared to methods based on local optimization and filters, our system can achieve the global optimum for coordinate initialization more stably and quickly, which is suitable for robots with size, weight, and power constraints. The source code is released for reference.

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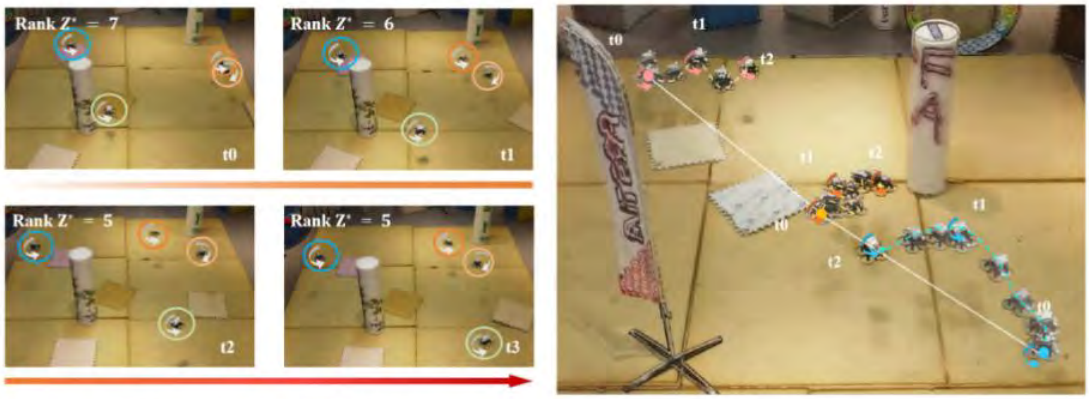

(a) Real-world experiments with 4 drones.

(b) Real-world experiments with 3 drones.

How NOKOV Contributes to the Research

To analyze errors in real-world experiments, we use the NOKOV Motion Capture System to get the ground truth of rotation estimation, including poses of all robots in the motion capture system coordinate.

Citation Li Y, Zhao A, Wang Y, et al. Fact: Fast and active coordinate initialization for vision-based drone swarms[J]. IEEE Robotics and Automation Letters, 2024.

Link https://ieeexplore.ieee.org/document/10803028

Fast UAV Object-Searching in Large-Scale and Complex Environments

Keywords

Hierarchical strategy, motion and path planning, object searching, unmanned aerial vehicle (UAV)

Abstract

Autonomous object-searching is crucial for various applications of unmanned aerial vehicles (UAVs). Considering the fact that existing autonomous exploration methods either focus only on maximizing the exploration of unknown areas or suffer from insufficient searches due to repeated and unnecessary exploration, this article introduces an effective object-searching strategy for UAVs in large-scale and complex environments. A novel method is proposed to empower UAVs with the capability to conduct fast, secure, and efficient searches for interested objects in large-scale and complex environments. A Kalman filter-based YOLO algorithm is first proposed to achieve robust object position estimation in cluttered and occlusion-prone scenarios, and a mode-based method is then introduced to conduct a computationally efficient viewpoint generation. A hierarchical searching method is proposed, which not only can increase computational and search efficiency but also can leverage frontier data for search-planning, including coarse global searching paths and optimizing local refined searching trajectories. Experimental results in six different environments indicate that our proposed method outperforms existing techniques in terms of both reduced searching times and computing time. Moreover, the effectiveness of the proposed method is substantiated in various real-world scenarios.

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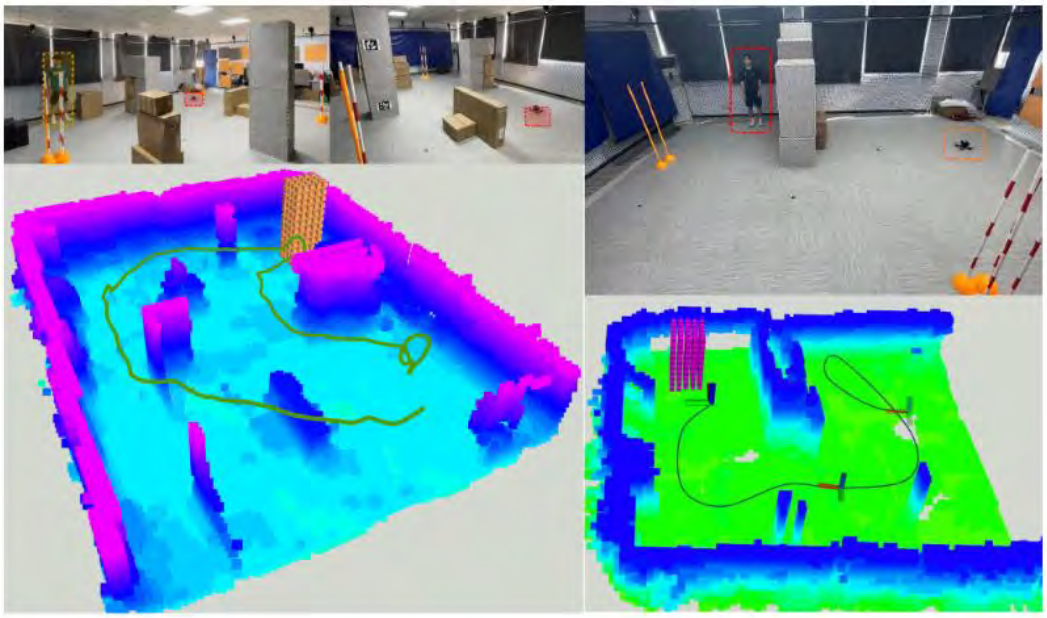

Fig. 10. Two search experiment results in different indoor scenarios, where the curve represents the UAV's flight trajectory.

How NOKOV Contributes to the Research

In the real-world search experiment, we localize the UAVby a visual-inertial state estimator\[40]and employ a NOKOVmotion capture system to validate the precision of this visual-inertial state estimator. The UAV platform is equipped with anIntel NUC11TNKi5, and the Intel RealSense Depth CameraD435i with the FOVs 87∘×58∘. This computer includes anIntel Core i5-1135G CPU and 32 GB of RAM.

Citation Lin H, Yang X, Wen G, et al. Fast UAV Object-Searching in Large-Scale and Complex Environments[J]. IEEE Transactions on Cybernetics, 2025.

Link https://ieeexplore.ieee.org/document/10973128

Finite-Time Fault-Tolerant Consensus of UAVs: A Switching Event-Triggered Fuzzy Control Scheme

Keywords

Fuzzy fault-tolerant cooperative control, finite-time consensus, switching event-triggered mechanism

Abstract

In finite-time consensus tracking (FCT) missions of unmanned aerial vehicles (UAVs), faults in aircraft actuators are crucial factors causing tracking precision degradation. In order to solve this problem, this paper develops a fuzzy fault-tolerant cooperative control scheme for UAVs to achieve FCT missions with predefined precision. Compared to existing results, the settling time formulation approach of consensus errors is significantly simplified, which facilitates operators to preset the settling time. Then a switching event-triggered mechanism is designed to flexibly change the transmission frequency of control signals, enabling the limited communication resources of UAVs to be reasonably consumed before and after the settling time. Based on the Lyapunov stability theory, it is proved that all signals of systems are bounded, and consensus errors can achieve prescribed precision in a finite time. Moreover, Zeno behavior is excluded. Finally, a simulation study demonstrates the efficiency and feasibility of the designed control scheme under various uncertainties. Note to Practitioners—In the existing FCT control schemes for UAVs, the formulation approaches of settling time depend on the structure of the communication network and the initial states of the aircraft, which hampers these schemes implemented in large-scale UAVs control tasks. How to effectively simplify the formulation approach of settling time has crucial practical significance and research value. In addition, since the communication bandwidth of UAVs is limited, the existing control strategies introduce event-triggered mechanisms to decrease the communication burden. However, adopting a single event-triggered mechanism cannot flexibly change the transmission frequency of control signals, which may make the limited communication resources fail to be reasonably consumed before and after the settling time. In order to solve the above problems, this paper develops a switching event-triggered FCT control scheme for UAVs, where the designed trigger mechanism can flexibly change the transmission frequency of control signals. Meanwhile, the settling time can be directly formulated following the wishes of operators.

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Fig. 4. PIXHAWK4-based experimental simulation platform.

How NOKOV Contributes to the Research

Furthermore, the experiment utilizes the NOKOV high-precision three-dimensional optical motion capture systemillustrated in Fig.4. This system comprises motion capturecameras, accessories (including reflective marker points, gim-bals, lens connection lines, and lens mounting devices), and Seeker motion capture software.

Citation Liang H, Chen L, Yang X, et al. Finite-time fault-tolerant consensus of UAVs: a switching event-triggered fuzzy control scheme[J]. IEEE Transactions on Automation Science and Engineering, 2024.

Link https://ieeexplore.ieee.org/document/10666795

Fixed-time bipartite flocking of perturbed networked UAV systems: A distributed optimization approach

Keywords

Self-organization performance, Distributed optimization, Bipartite flocking, Networked UAV systems, Fixed-time convergence

Abstract

Flocking, inspired by the collective dynamics observed in biological swarms, exemplifies the emergence of self-organization and swarm intelligence through local agent interactions. Motivated by these principles, this paper investigates the fixed-time bipartite flocking control problem for networked unmanned aerial vehicle (UAV) systems under external disturbances from the perspective of distributed optimization. The proposed solution addresses key concerns in multi-agent coordination, including the emergence rate of flocking behavior, robustness against uncertainties, and performance optimization. A hierarchical distributed optimal control framework is developed, consisting of a distributed optimization layer and a trajectory tracking layer. Theoretically, the proposed control scheme ensures (i) convergence to the global optimum of the distributed optimization problem within a fixed time, and (ii) fixed-time emergence of bipartite flocking behavior characterized by subgroup cohesion and velocity alignment. The stability of the closed-loop system is rigorously established via a Lyapunov-based analysis method, which also guarantees robustness against dynamic disturbances. In addition, explicit upper bounds on the settling time for both layers are derived, allowing the trade-off between convergence speed and control effort to be tuned through parameter selection. Finally, numerical simulations together with real-world experiments are presented to validate the effectiveness and practical feasibility of the proposed fixed-time bipartite flocking control scheme.

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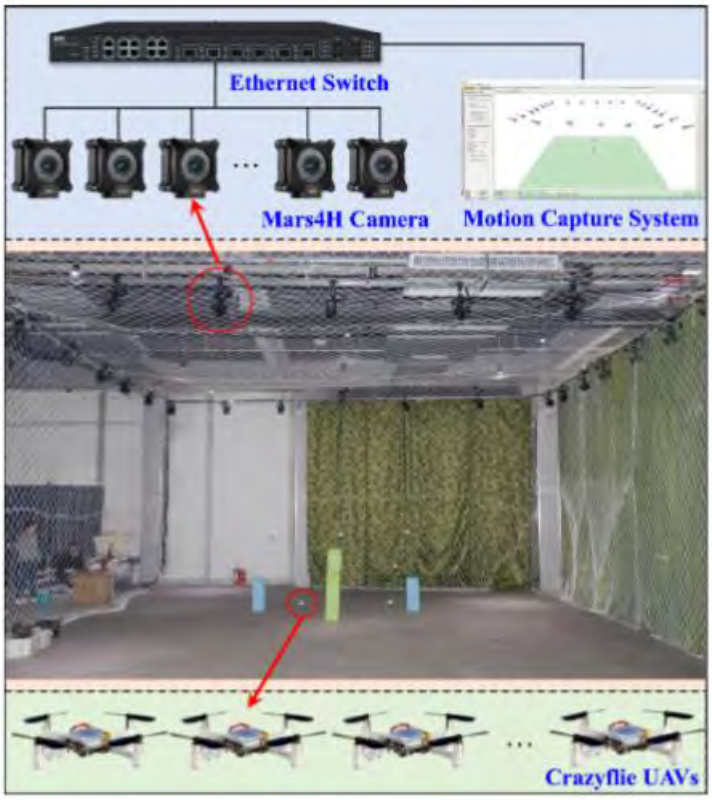

Fig. 6. The experiment platform based on NOKOV motion capture system and Crazyflie UAVs.

How NOKOV Contributes to the Research

5.Numerical simulations and experimental validation
This section validates the effectiveness of the proposed distributedoptimization-based bipartite flocking control scheme through both numerical simulations and real-world experiments. The simulation studyis conducted using the MATLAB platform, while the experimental evaluation is performed with Crazyflie UAVs in conjunction with the NOKOV motion capture system.

Citation Li W, Shi M, Shi L, et al. Fixed-time bipartite flocking of perturbed networked UAV systems: A distributed optimization approach[J]. Expert Systems with Applications, 2026, 299: 129979.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001602407900001

Fixed-Time Sliding-Mode Lateral-Longitudinal Control for Vehicle Platoon With Strict Lane Constraints and Recoverable Spacing Policy

Keywords

Fixed-time sliding-mode control, lane constraint, lateral-longitudinal control, vehicle platoon

Abstract

This paper investigates the lateral and longitudinal platoon control problem under user-specified lane and inter-vehicle spacing constraints. By modeling in the Frenét Frame, the lateral and longitudinal movements of the vehicles are decomposed. A novel lateral control strategy is proposed to strictly enforce a preset lane departure accuracy by transforming lane constraints into heading angle constraints. In the longitudinal control, considering the presence of a non-ideal leading vehicle, a prescribed performance controller is designed to regulate its velocity. Additionally, a longitudinal control strategy based on a double-ended smooth transition function is proposed to mitigate the effects of non-zero initial errors and restore the standard constant time headway policy after a preset time. To guarantee practical fixed-time stability, a continuous variable exponent coefficient fixed-time sliding surface is constructed, and adaptive sliding mode controllers are designed. The effectiveness of the proposed method is validated through both simulations and experiments. The source code is available on GitHub (https://github.com/Mudianrui/FSC-VPuLLC.git) to support further research on lateral-longitudinal platoon control.

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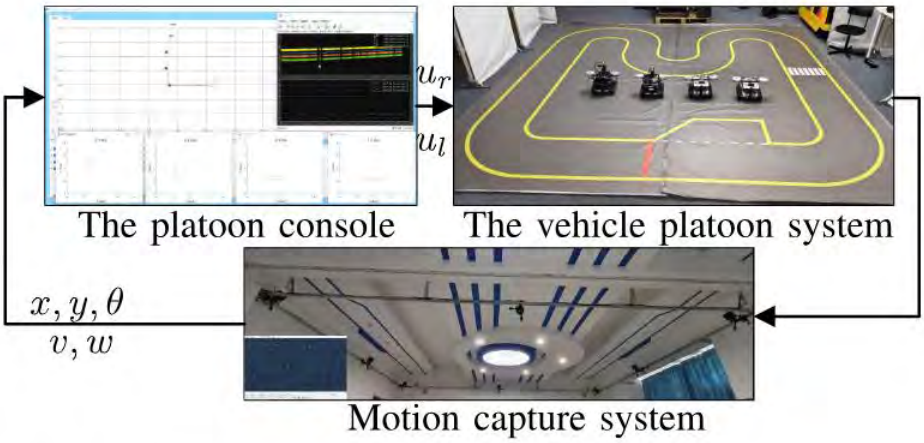

Fig. 5. The overall structure of the experimental platform.

How NOKOV Contributes to the Research

The lane used in the experiment is same as (44) withL =0.5,l=2.5,=2.4,l'= 0.17,1= 0.4. The overallstructure of the experimental platform is shown in Fig. 5., which is composed of the motion capture systems, the vehicleplatoon system, and the platoon console. The NOKOV motion capture system is used to collect the position and attitudeof the vehicles. The platoon console is composed of theself-developed vehicles command and control system andMatlab. In experiments, the vehicles are connected to theplatoon console via a wireless network, and the proposedcontroller runs in Matlab while collecting experimental data.

Citation Mu, Dianrui, et al. "Fixed-Time Sliding-Mode Lateral-Longitudinal Control for Vehicle Platoon With Strict Lane Constraints and Recoverable Spacing Policy." IEEE Transactions on Intelligent Transportation Systems (2025).

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001512676500001

Flexible Affine Formation Control Based On Dynamic Hierarchical Reorganization

Keywords

Hierarchical reorganization, affine formation control, power smooth transition, swarm

Abstract

Current formations commonly rely on invariant hierarchical structures, such as predetermined leaders or enumerated formation shapes. These structures could be unidirectional and sluggish, constraining their flexibility and agility when encountering cluttered environments. To surmount these constraints, this work proposes a dynamic hierarchical reorganization approach with affine formation. Central to our approach is the fluid leadership and authority redistribution, for which we develop a minimum time-driven leadership evaluation algorithm and a power transition control algorithm. These algorithms facilitate autonomous leader selection and ensure smooth power transitions, enabling the swarm to adapt hierarchically in alignment with the external environment. Extensive simulations and real-world experiments validate the effectiveness of the proposed method. The formation of five aerial robots successfully performs dynamic hierarchical reorganizations, enabling the execution of complex tasks such as swerving maneuvers and navigating through hoops at velocities of up to 1.05m/s. Comparative experimental results further demonstrate the significant advantages of hierarchical reorganization in enhancing formation flexibility and agility, particularly during complex maneuvers such as U-turns. Notably, in the aforementioned real-world experiments, the proposed method reduces the flight path length by at least 33.8% compared to formations without hierarchical reorganization.

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Fig. 3. Environment and hardware setup. (a) A scenario set within an obstacle-free dark environment. (b) An environment featuring two hoop obstacles. (c) The hardware system mounted on the aerial swarm.

How NOKOV Contributes to the Research

Moreover, the NOKOV® motion capture system provides the global position measurements, and an UP Board 4000® computing board running ROS is adopted as the onboard computer. A small TP-LINK® router model TL-WDR5650 is mounted on each drone to facilitate communication among multiple drones. Each drone is equipped with a light strip, controlled via GPIO on the UP Board 4000® computing board. This setup allows for visualizing the hierarchical reorganization process within the swarm. When a drone's light strip is illuminated, it indicates that the drone is the current leader of the formation.

Citation Li, Yuzhu, and Wei Dong. "Flexible affine formation control based on dynamic hierarchical reorganization." IEEE Robotics and Automation Letters (2024).

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001351578600003

FLOAT Drone: A Fully-actuated Coaxial Aerial Robot for Close-Proximity Operations

Abstract

How to endow aerial robots with the ability to operate in close proximity remains an open problem. The core challenges lie in the propulsion system's dual-task requirement: generating manipulation forces while simultaneously counteracting gravity. These competing demands create dynamic coupling effects during physical interactions. Furthermore, rotor-induced airflow disturbances critically undermine operational reliability. Although fully-actuated unmanned aerial vehicles (UAVs) alleviate dynamic coupling effects via six-degree-of-freedom (6-DoF) force-torque decoupling, existing implementations fail to address the aerodynamic interference between drones and environments. They also suffer from oversized designs, which compromise maneuverability and limit their applications in various operational scenarios. To address these limitations, we present FLOAT Drone (FuLly-actuated cOaxial Aerial roboT), a novel fully-actuated UAV featuring two key structural innovations. By integrating control surfaces into fully-actuated systems for the first time, we significantly suppress lateral airflow disturbances during operations. Furthermore, a coaxial dual-rotor configuration enables a compact size while maintaining high hovering efficiency. Through dynamic modeling, we have developed hierarchical position and attitude controllers that support both fully-actuated and underactuated modes. Experimental validation through comprehensive real-world experiments confirms the system's functional capabilities in close-proximity operations.

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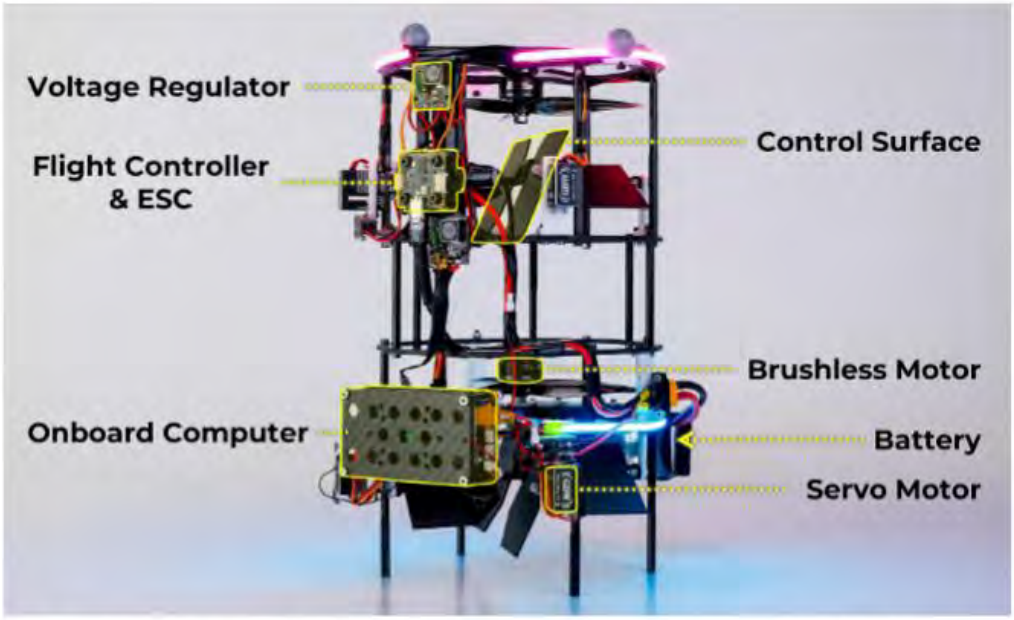

Fig. 5: Prototype and hardware configuration of FLOAT Drone.

How NOKOV Contributes to the Research

In all subsequent experiments, the robot's position and pose estimation are obtained from a NOKOV motion capture system. The FLOAT Drone is capable of operating in both fully-actuated and underactuated flight modes, achieving a balance between flying performance and energy efficiency. The underactuated mode can only activate four actuators, resulting in energy savings compared to full actuation mode. Additionally, the simplified control framework enables easier implementation of high-speed flight. On the other hand, while the fully-actuated mode requires more complex planning and control algorithms, its decoupled thrust vector characteristics provide higher control precision for closerange operational tasks.

Citation J. Lin, S. Ji, Y. Wu, T. Wu, Z. Han and F. Gao, "FLOAT Drone: A Fully-actuated Coaxial Aerial Robot for Close-Proximity Operations," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 7216-7223, doi: 10.1109/IROS60139.2025.11245967.

Link https://ieeexplore.ieee.org/document/11245967

Flying Co-Stereo: Enabling Long-Range Aerial Dense Mapping via Collaborative Stereo Vision of Dynamic-Baseline

Keywords

Collaborative visual mapping, dynamic stereo baseline, flying robots.

Abstract

For unmanned aerial vehicle (UAV) swarms operating in large-scale unknown environments, lightweight long-range mapping is crucial for enhancing safe navigation. Traditional stereo cameras constrained by a short fixed baseline suffer from limited perception ranges. To overcome this limitation, we present flying collaborative stereo (flying co-stereo), a cross-agent collaborative stereo vision system that leverages the wide-baseline spatial configuration of two UAVs for long-range dense mapping. However, realizing this capability presents several challenges. First, the independent motion of each UAV leads to a dynamic and continuously changing stereo baseline, making accurate and robust estimation difficult. Second, efficiently establishing feature correspondences across independently moving viewpoints is constrained by the limited computational capacity of onboard edge devices. To tackle these challenges, we introduce the flying co-stereo system within a novel collaborative dynamic-baseline stereo mapping (CDBSM) framework. We first develop a dual-spectrum visual-inertial-ranging estimator to achieve robust and precise online estimation of the baseline between the two UAVs. In addition, we propose a hybrid feature association strategy that integrates cross-agent feature matching—based on a computationally intensive yet accurate deep neural network—with intra-agent, optical-flow-based lightweight feature tracking. Furthermore, benefiting from the wide baselines between the two UAVs, our system accurately recovers long-range covisible 3-D sparse points. We then employ a monocular depth network to predict up-to-scale dense depth maps, which are refined using accurate metric scales derived from the triangulated sparse points via exponential fitting. Extensive real-world experiments demonstrate that the proposed flying co-stereo system achieves robust and accurate dynamic baseline estimation in complex environments while maintaining efficient feature matching with resource-constrained computers under varying viewpoints. Ultimately, our system achieves dense 3-D mapping at distances of up to 70 m with a relative error between 2.3% and 9.7%. This corresponds to up to a 350% improvement in maximum perception range and

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up to a 450% increase in coverage area compared to conventional stereo vision systems with fixed compact baselines.

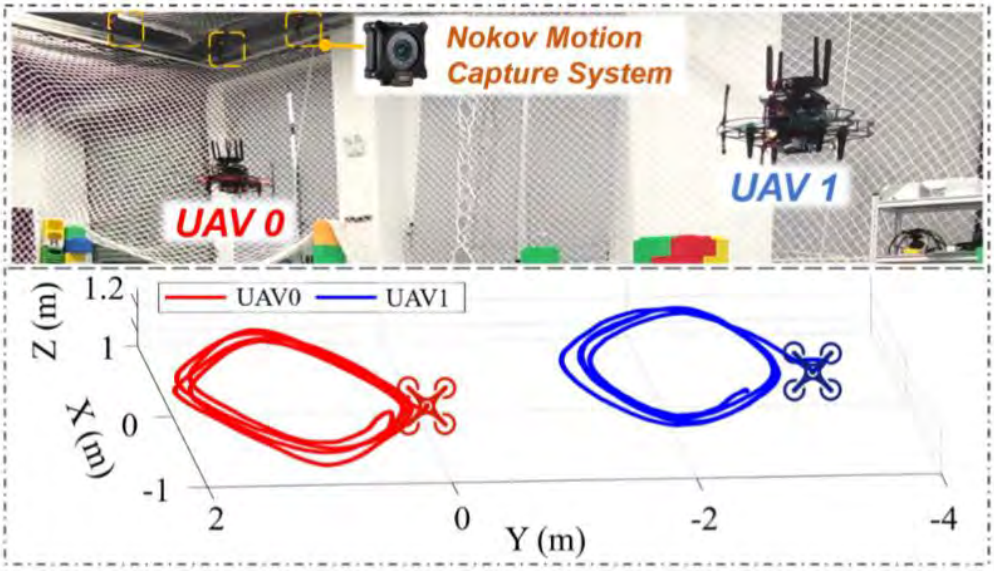

Fig. 10. Experiments for relative pose estimation of Flying Co-Stereo under the motion capture system.

How NOKOV Contributes to the Research

Indoor accuracy is evaluated via a NOKOV motion capture system (see Fig. 10). Both UAVs autonomously fly synchronized circular trajectories in the ENU frame ((x)-forward, (y)-left, (z)-up) with a 3 m baseline. We assess DS-VIRE (relative pose estimation) against two baselines: a visual PnP method (using only inter-UAV observations) and VIO differencing \[74] (deriving relative pose by subtracting individual UAV VIO poses).

Citation Wang, Z., Zuo, X., & Dong, W. (2026). Flying Co-Stereo: Enabling Long-Range Aerial Dense Mapping via Collaborative Stereo Vision of Dynamic-Baseline. IEEE Transactions on Robotics.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001694353900008

FORESEER: Recognize and utilize uncertainties by integrating data-based learning and symbolic feedback

Keywords

learning for planning and control, uncertainty prediction, uncertainty utilization, unmanned aerial vehicle

Abstract

Uncertainties resulting from intricate internal model uncertainties and external environmental disturbances significantly degrade robot planning and control performance. However, recognizing such persistently varying uncertainties in an explainable and lightweight manner is exceptionally challenging. We present two converged uncertainty prediction frameworks through the Fusion of Online Reactive Estimation and Sustained Experience Exploitation for Robots (FORESEEER), enabling accurate prediction of two general kinds of uncertainties. Both frameworks feature properties of precision, lightweight, universality, and stability, in comparison with existing solutions. At first, a prediction algorithm for nonlinearly parametric uncertainties is developed by merging analytical basis learning with online symbolic adaptive estimation. Furthermore, an online prediction algorithm for more challenging composite uncertainties is proposed by seamlessly integrating learning-based feedforward and model-based/symbolic feedback observer. Benchmark comparisons on flying drones showcase the accuracy of the FORESEEER on various real uncertainties including mass, aerodynamic drag, rain, and rope tension, leading to subsequent high-precision control. Moreover, an energy-saving and time-saving planning strategy is presented by utilizing the favorable wind. The developed algorithms hold the promising potential for direct combination with existing planning/control algorithms, promoting the environmental adaptability of robots.

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Figure 1. Application scenarios of the FORESEER. Five types of drones are employed in this work. (a) A drone with a gripper (named capturer) is commanded to capture an unknown target and fly indoors and outdoors. (b) The algorithm trained for the capturer is generalized to a small faster drone seamlessly. (c) A waterproof drone flies under the high aerodynamic drag and rain disturbance. A foam board is attached to increase the drag. (d) Planning an energy-saving and time-saving trajectory by utilizing the external wind. (e) A flying drone drags a car with an inelastic rope, which tension changes rapidly. The mass uncertainty in a and b is a kind of parametric uncertainty, while uncertainties in c–e belong to more challenging composite uncertainties affected by both internal and external time-varying factors. By employing our developed algorithms, the above uncertainties can be precisely captured from limited measurements and computing resources. We refer to the Project Site for more experimental details.

How NOKOV Contributes to the Research

Test results. In tests, the Capturer is commanded to grasp a target (0.427 kg) indoor, maneuver in a fast trajectory (8-figure with 6 m × 4 m area and 8 s period), and drop the target halfway, as depicted by Figure 5(a). The location state of the drone is provided by the NOKOV motion capture system. The estimated uncertainty is compensated by the baseline controller in a feedforward manner. In order to examine the extrapolation ability of the learned uncer-tainty model, the mass of the battery (0.759 kg) is also considered to be part of the total unknown mass along with the grasped target, leading to 1.186 kg mass un-certainty totally, which is beyond the scope of the training dataset (0.1 0.7 kg). Moreover, the maximum flight speedinthe Y-axiscanreach3.14m/s,which is also beyond the scope of the training dataset (0 3m/s).Apart from the baseline controller without the compensation of estimated uncertainty, the feedback-based method, DO (Chen et al., 2016), is also taken as a comparison, which has a decent estimation performance for slow-varying disturbance (Appendix D)

Citation Jia J, Guo K, Wang Y, et al. FORESEER: Recognize and utilize uncertainties by integrating data-based learning and symbolic feedback[J]. The International Journal of Robotics Research, 2024: 02783649251364000.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001586397700001

Formation tracking theory and experiment for leader-following quadrotor swarm under optical motion capture localization system

Keywords

Leader-following formation, Quadrotor swarm, Control strategy, Tracking experiment

Abstract

The formation tracking approach and the flight experiment for a quadrotor swarm with the leader-following interactive topology are investigated, where it is required that following quadrotors with a specific geometric structure track the state of the leading quadrotor. Firstly, by dividing the interactive topology into the leader-following interactive relationship and the following interactive relationship, the control strategies of the leading and following quadrotors are proposed, respectively. Then, a formation tracking achievability criterion for a quadrotor swarm is proposed by constructing a new Lyapunov function, where two control gains are given in an analytic form. Finally, an algorithm for a quadrotor swarm to realize formation tracking is proposed, where the control strategy is used to determine the outer-loop position control quantity, and a formation tracking flight experiment is performed under the indoor optical motion capture location system to demonstrate the effectiveness of theoretical conclusions.

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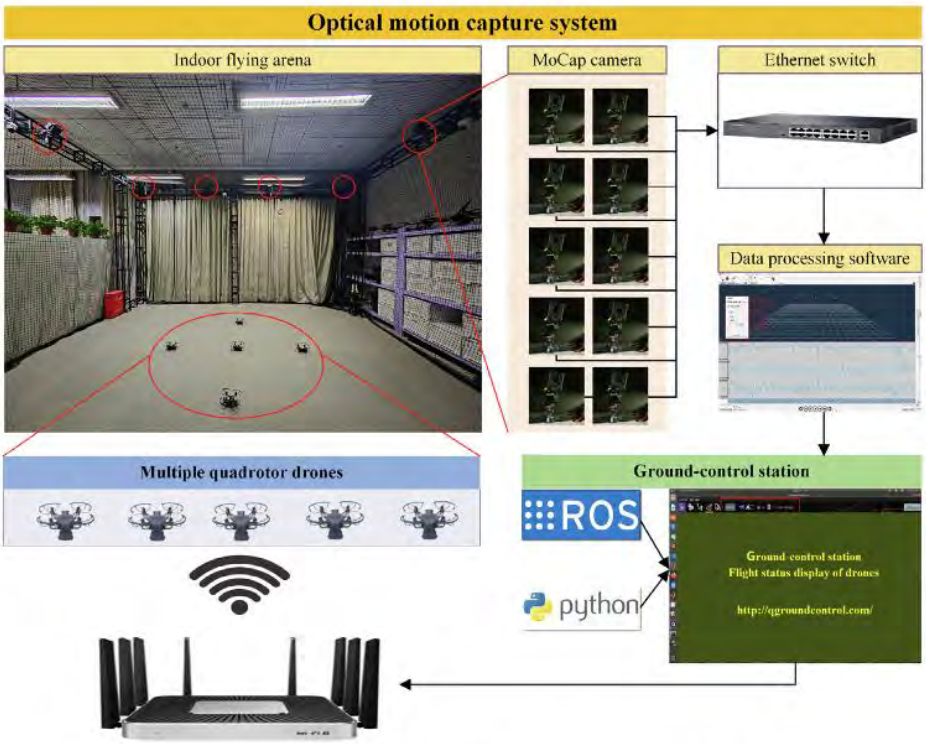

Fig. 3. Main composition of formation flight experimental platform.

How NOKOV Contributes to the Research

The main components of the formation flight experimental platform are shown in Fig. 3, which contain three main parts: an optical motion capture localization system, a ground-control system, and five quadro tors. The optical motion capture localization system is composed of ten motion capture cameras installed uniformly on a steel protective frame, an Ethernet switch, and a data processing software. The infrared images of the reflective marker balls on the quadrotors are dynamically ob tained by the motion capture cameras, and the movement information of the quadrotors can be calculated by constructing a three-dimensional spatial motion observation model in the data processing software, its positioning accuracy can reach less than 1 mm.

Citation Dang H, Guo S, Xi J, et al. Formation tracking theory and experiment for leader-following quadrotor swarm under optical motion capture localization system[J]. Robotics and Autonomous Systems, 2025, 186: 104918.

Link https://www.sciencedirect.com/science/article/abs/pii/S0921889025000041

Gazing Preference Induced Controllable Milling Behavior in Swarm Robotics

Keywords

Collective behavior, milling, gazing preference, swarm robots

Abstract

Milling is a collective behavior that is useful in a variety of real scenarios, but how to regulate milling behavior simply and efficiently is still a challenging problem. This letter introduces a novel method for controlling milling behavior in real-world robots, where both the direction and radius of the milling pattern can be continuously adjusted by tuning a single parameter. Inspired by visual attention mechanisms, the proposed model introduces the concept of gazing preference. That is, the robot will prefer to choose a neighbor in a particular direction for interaction, which in turn creates a force that deviates from the direction of velocity and leads to the milling behavior. Additionally, a potential function ensures swarm cohesion and prevents collisions through simulated repulsive and attractive forces. Simulations and experiments involving up to 50 robots demonstrate that adjusting the gazing preference parameter enables seamless control of the rotation direction and fine-tuning of the milling pattern's angular velocity and radius. Overall, this letter provides a straightforward and effective approach for designing controlled milling behavior in swarm robotics.

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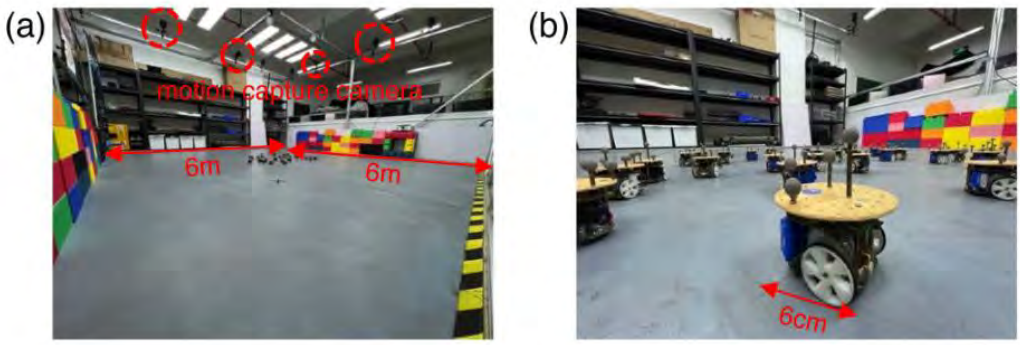

Fig. 7. The SwarmBang system. (a) Square experiment field with a length of 6 meters. We use a motion capture camera system to locate the position of robots. (b) Wheeled robot with a diameter of 6 centimeters.

How NOKOV Contributes to the Research

We conduct our experiments in an area of6m×6m, with robot positions tracked by the NOKOV motion capture camera system. These positions are sent to a central computer that simultaneously runs the collective model. The control signals, calculated using Eq.(2), are then broadcast to each robot via a 2.4 GHz module. It should be noted that although the proposed model can be implemented in a distributed manner, our physical experiments are centralized because the robot does not yet have distributed sensing capabilities.

Citation Zhou, Y., Song, J., Liu, T., & Peng, X. (2025). Gazing preference induced controllable milling behavior in swarm robotics. IEEE Robotics and Automation Letters.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001479448500031

Global-State-Free Obstacle Avoidance for Quadrotor Control in Air-Ground Cooperation

Keywords

Obstacle avoidance, air-ground cooperation, non-inertial model, modulated dynamical system

Abstract

CoNi-MPC [Zhang et al. (2023)] provides an efficient framework for UAV control in air-ground cooperative tasks by relying exclusively on relative states, eliminating the need for global state estimation. However, its lack of environmental information poses significant challenges for obstacle avoidance. To address this issue, we propose a novel obstacle avoidance algorithm, Cooperative Non-inertial frame-based Obstacle Avoidance (CoNi-OA), designed explicitly for UAV-UGV cooperative scenarios without reliance on global state estimation or obstacle prediction. CoNi-OA uniquely utilizes a single frame of raw LiDAR data from the UAV to generate a modulation matrix, which directly adjusts the quadrotor's velocity to achieve obstacle avoidance. This modulation-based method enables real-time generation of collision-free trajectories within the UGV's non-inertial frame, significantly reducing computational demands (less than 5 ms per iteration) while maintaining safety in dynamic and unpredictable environments. The key contributions of this work include: 1) a modulation-based obstacle avoidance algorithm specifically tailored for UAV-UGV cooperation in non-inertial frames without global states; 2) rapid, real-time trajectory generation based solely on single-frame LiDAR data, removing the need for obstacle modeling or prediction; and 3) adaptability to both static and dynamic environments, thus extending applicability to featureless or unknown scenarios.

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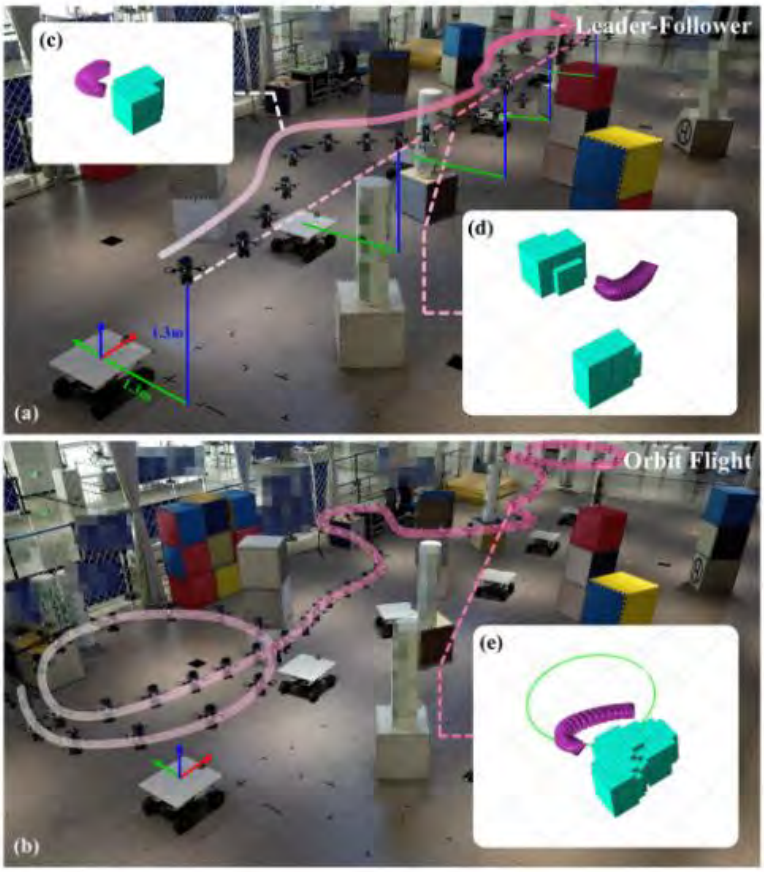

Fig. 9. Obstacle avoidance flight of the quadrotor during (a) leader-following and (b) orbit-flight tasks. (c)–(e) show the generated collision-free trajectories when the quadrotor encounters obstacles.

How NOKOV Contributes to the Research

The UAV and UGV platforms used are shown in Fig.6alongwith their dimensions. The relative state estimation is com-puted from the NOKOV motion capture system. The quadrotor,with a weight of 974.4 g, achieves a thrust-to-weight ratio of2.78 when powered by a 6S battery. Trajectory generation and CoNi-MPC are implemented on an onboard computer with anIntel N100 processor (up to 3.40 GHz) and 16 GB of RAM,while the Livox Mid-360 provides the sampled data points.

Citation Zhang B, Chen X, Chen Q, et al. Global-State-Free Obstacle Avoidance for Quadrotor Control in Air-Ground Cooperation[J]. IEEE Robotics and Automation Letters, 2025.

Link https://ieeexplore.ieee.org/document/10993292

HARP: 3-DoF High-Update-Rate Acoustic Rigid-Body Positioning

Keywords

Acoustic indoor positioning, high update rate, rigid-body localization (RBL) signal detection, time difference of arrival (TDOA)

Abstract

Acoustic indoor positioning has been widely studied due to its advantages of low cost, easy deployment, and high accuracy. However, the limitation of insufficient update rates remains a challenge for its application in mobile target localization and navigation. To tackle the obstacles, this article presents high-update-rate acoustic rigid-body positioning (HARP). HARP employs a combined frequency-division multiple access (FDMA) and code-division multiple access (CDMA) signal scheme, achieving stable signal detection at 50 Hz based on an optimal pairing initialization process and a constraint-enhanced cross correlation (CE-CC) detection algorithm. Furthermore, HARP is capable of achieving three-degree-of-freedom (3-DoF) estimation, including planar position and target heading, using only two anchors. HARP updates the initial position (IP) using three-point collinearity rigid-body localization (TPC-RBL) and converts time difference of arrival (TDOA) into time-of-arrival (TOA) observations via continuous distance increment (CDI), enabling localization without synchronization between anchors and sensors. Real-world experiments validate the system's signal detection capability and localization accuracy. HARP achieves a 50-Hz update rate, significantly surpassing existing acoustic systems, while attaining an average localization accuracy of 38.8 mm and an angular accuracy of 6.42° within a room-scale area. This system provides a promising solution for low-cost indoor rigid-body localization (RBL) of mobile targets.

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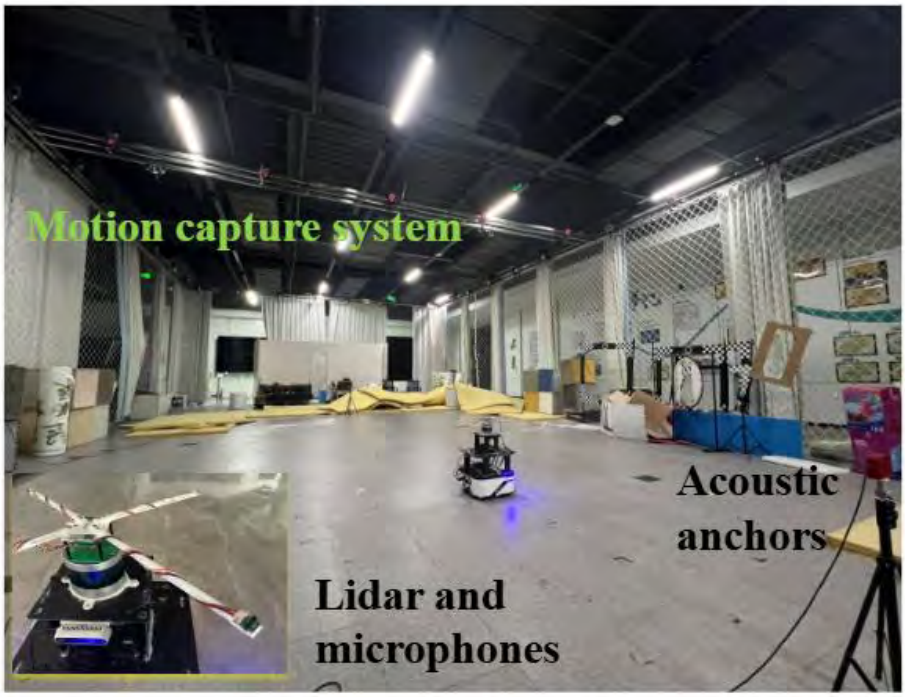

Fig. 14: Experimental setup.

How NOKOV Contributes to the Research

We have built a prototype of HARP system for performanceevaluation. We installed a microphone array consisting of4 micro-electro-mechanical system (MEMS) silicon microphones on a mobile platform, with dimensions of 39.1 cm×39.1 cm; meanwhile, we used two synchronized JBLGO2 Bluetooth speakers with a rated power of only 3.1Was anchors. To analyze the performance of the rigid bodypositioning system with a 50 Hz high update rate, we use the NOKOV motion capture system to provide the ground truth.

Citation Xi Y, Cui W, Liu G, et al. HARP: 3-DoF High-Update-Rate Acoustic Rigid-Body Positioning[J]. IEEE Sensors Journal, 2025.

Link https://ieeexplore.ieee.org/document/11062479

Heterogeneous Targets Trapping With Swarm Robots by Using Adaptive Density-Based Interaction

Keywords

Distributed robot systems, heterogeneous targets trapping, multirobot systems, swarm

Abstract

Homogeneous swarm robots are of significant research interest due to their robustness, flexibility, and scalability in completing complex tasks across various applications. This article focuses on trapping heterogeneous targets using swarm robots, with emphasis on their different strengths. These targets consist of weak, strong, and group-moving individuals, where stronger targets exhibit larger body size, higher physical strength, and stronger resistance ability. Our goal is to develop an adaptive controller that enables swarm robots to self-organize and distribute themselves to trap targets, while adjusting encirclement thickness and robot group size based on target strength. We leverage local implicit information generated from density-based interaction to improve interrobot and robot–target interactions through adaptive allocation and transformation mechanisms. The feasibility of our approach is validated through numerical simulations and experiments involving up to 50 physical robots and one human-controlled transformer.

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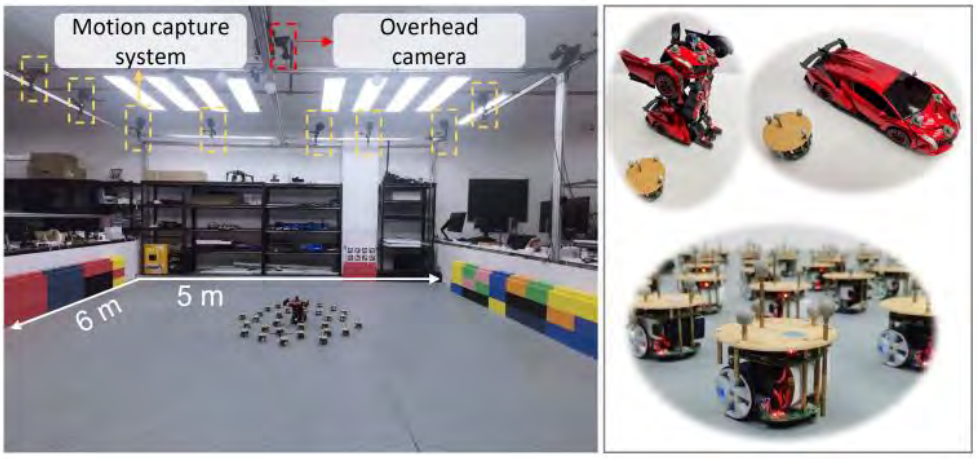

Fig. 9. The SwarmBang robot, human-controlled transformer and experimental site.

How NOKOV Contributes to the Research

Our team has developed the SwarmBang robot, a teacup-sized mobile robot (approximately60 mm×60 mm×60 mm)with differential-wheeled drive, designed for self-organizedand collective behavior studies, as shown in Fig. 9. Our experiments are conducted in an area of 5000 mm × 6000 mm,and we use a motion capture system manufactured by NOKOVto track the positions and headings of all robots.

Citation Zhang S, Lei X, Peng X, et al. Heterogeneous targets trapping with swarm robots by using adaptive density-based interaction[J]. IEEE Transactions on Robotics, 2024, 40: 2729-2748.

Link https://ieeexplore.ieee.org/abstract/document/10506641

Heteroscedastic Bayesian Optimization-Based Dynamic PID Tuning for Accurate and Robust UAV Trajectory Tracking

Abstract

Unmanned Aerial Vehicles (UAVs) play an important role in various applications, where precise trajectory tracking is crucial. However, conventional control algorithms for trajectory tracking often exhibit limited performance due to the underactuated, nonlinear, and highly coupled dynamics of quadrotor systems. To address these challenges, we propose HBO-PID, a novel control algorithm that integrates the Heteroscedastic Bayesian Optimization (HBO) framework with the classical PID controller to achieve accurate and robust trajectory tracking. By explicitly modeling input-dependent noise variance, the proposed method can better adapt to dynamic and complex environments, and therefore improve the accuracy and robustness of trajectory tracking. To accelerate the convergence of optimization, we adopt a two-stage optimization strategy that allows us to more efficiently find the optimal controller parameters. Through experiments in both simulation and real-world scenarios, we demonstrate that the proposed method significantly outperforms state-of-the-art (SOTA) methods. Compared to SOTA methods, it improves the position accuracy by 24.7% to 42.9%, and the angular accuracy by 40.9% to 78.4%.

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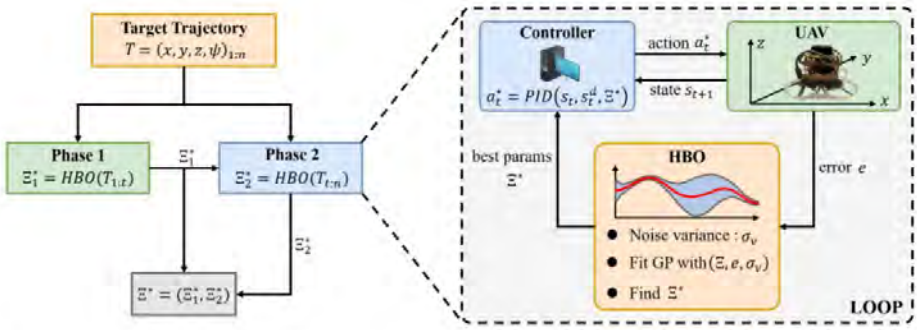

Fig. 1. Overall algorithm framework and controller parameter optimization, we first divide the trajectory tracking into two phases and use heteroskedastic Bayesian optimization to search for the optimal PID parameters in each phase to adaptively obtain the best parameter configuration for the current trajectory.

How NOKOV Contributes to the Research

To validate the proposed method, we carried out realworld experiments using a quadrotor UAV equipped with a nonlinear controller, operating under the NOKOV motion capture system. The quadrotor UAV used in the experiments had a mass of 800 grams(g), a maximum thrust of 2.99 Newtons(N), and a minimum thrust of 0.22 Newtons(N). The controller parameters were optimized using the approach described in this work. The experimental platform was built on the open-source hardware OminiNxt, and the Px4 controller was employed to track the commanded collective thrust and body rates. The experiments were conducted within a motion capture system with a measurement volume of6 × 4 × 3 meters. The system operated at a frequency of 100 Hz, providing accurate position and attitude measurements for the UAV during the experiments.

Citation F. Gu et al., "Heteroscedastic Bayesian Optimization-Based Dynamic PID Tuning for Accurate and Robust UAV Trajectory Tracking," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 17428-17435, doi: 10.1109/IROS60139.2025.11247487.

Link https://ieeexplore.ieee.org/document/11247487

HHPSO: A Heuristic Hybrid Particle Swarm Optimization Path Planner for Quadcopters

Keywords

particle swarm optimization, path planning, motion capture, unmanned aerial vehicles (UAVs), aerial systems, applications

Abstract

Path planning for quadcopters has been proven to be one kind of NP-hard problem with huge search space and tiny feasible solution range. Metaheuristic algorithms are widely used in such types of problems for their flexibility and effectiveness. Nevertheless, most of them cannot meet the needs in terms of efficiency and suffer from the limitations of premature convergence and local minima. This paper proposes a novel algorithm named Heuristic Hybrid Particle Swarm Optimization (HHPSO) to address the path planning problem. On the heuristic side, we use the control points of cubic b-splines as variables instead of waypoints and establish some heuristic rules during algorithm initialization to generate higher-quality particles. On the hybrid side, we introduce an iteration-varying penalty term to shrink the search range gradually, a Cauchy mutation operator to improve the exploration ability, and an injection operator to prevent population homogenization. Numerical simulations, physical model-based simulations, and a real-world experiment demonstrate the proposed algorithm' s superiority, effectiveness and robustness.

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How NOKOV Contributes to the Research

And for the real-drone experiment, we choose NOKOV motion caputrue system as the global location system and use Bitcraze Crazyflie 2.1 nano-quadrotors as the flying platform for its characteristics of small volume (9cm rotor-to-rotor), lightweight (34 g), and suitable for indoor flying.

Citation Lou J, Ding R, Wu W. HHPSO: A Heuristic Hybrid Particle Swarm Optimization Path Planner for Quadcopters[J]. Drones, 2024, 8(6): 221.

Link https://www.mdpi.com/2504-446X/8/6/221

Incomplete Information-Based Resilient Strategy Design for Cyber-Physical Systems Under Stochastic Communication Protocol

Keywords

Bayesian game, cyber-physical system (CPS), incomplete information, jamming attack, Q-learning

Abstract

In this article, a novel resilient control strategy is proposed for a jammed cyber-physical system (CPS) with multiple transmission channels. In the presence of jamming attacks, the control performance of the time-varying system with nonlinear disturbances degrades due to the missing of the control command. To reduce the probability of being attacked, a novel multichannel transmission mechanism under a stochastic protocol is constructed, which can protect the information of which channel is selected from being known by the opponent. An incomplete information-based Bayesian game is introduced to describe the interaction of the control command transmitter and jamming attacker by means of taking both the control performance and energy consumption into consideration. Solutions for the dynamic Bayesian game are explored with the Q-learning method. The presented results for the jammed CPS are demonstrated via a helicopter system and a wheeled mobile robot platform.

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Fig. 6. Wheeled mobile robot platform.

How NOKOV Contributes to the Research

The platform is shown in Fig.6, whichconsists of E-pucks and a Nokov motion capture system with12 cameras to provide location and attitude information in real-time. We aim to control one E-puck from location(1.1m,0m)to(0m,0m). The optimal control gain is computed by solvingbackward Riccati-like recursion in MATLAB on a PC.

Citation Yuan H, Yuan Y, Zhong Y, et al. Incomplete information-based resilient strategy design for cyber-physical systems under stochastic communication protocol[J]. IEEE Transactions on Industrial Electronics, 2024, 71(11): 14967-14976.

Link https://ieeexplore.ieee.org/document/10443773

Information Fusion for Positioning System With Location Constraint of Camera and UWB

Keywords

Information Fusion for Positioning System With Location Constraint of Camera and UWB

Abstract

In this paper, a fusion estimator is investigated for positioning systems with location constraint of a camera and an ultra-wideband (UWB). Local camera and UWB estimators are designed independently for positioning with missed detections and local UWB estimates are aligned to local camera estimates for fusion estimation. Next the location constraint of the camera and UWB is transformed to a state constraint by state extension, and a constrained estimation projection method is applied to construct a fusion estimator. To measure the accuracy of the designed constrained fusion estimator, it is demonstrated that the estimation error covariance of the proposed method is equal to that of the matrix-weighted fusion method. Moreover, it is found that the proposed method has significant advantages over the matrix-weighted fusion method in computational cost, which is crucial for the real-time requirements of perception systems. Finally, the effectiveness of the proposed fusion estimator is displayed by simulation results and experimental results on the positioning system for an Ackerman vehicle. Note to Practitioners — The proposed method aims to solve the challenges of missed detections and different location coordinates from two sensors in the positioning systems. The paper introduces independently designed local estimators for both the camera and UWB sensors, which are capable of handling missed detections. The local UWB estimates are aligned with the local camera estimates to ensure that local estimates from two sensors are time-aligned in the fusion process. The location constraint of the sensors is transformed into a state constraint through state extension for constructing the fusion estimator with the constrained estimation projection method. The paper demonstrates that the estimation error covariance of the proposed fusion estimator is equivalent to that of the traditional matrix-weighted fusion method. Moreover, the proposed method offers significant advantages in terms of computational cost, which is critical for real-time performance in perception systems. Practitioners can use the proposed fusion estimator to enhance the accuracy and reliability of positioning systems that incorporate two different sensors with missed detections and location constraint. The method is particularly well-suited for applications where real-time performance is a requirement.

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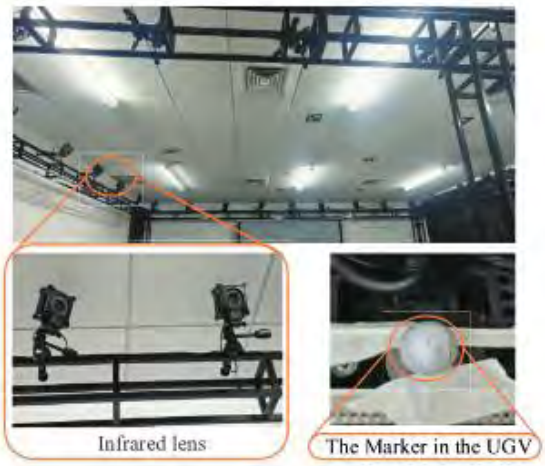

Fig. 16. The Nokov optical motion capture system (NOMCS) platform.

How NOKOV Contributes to the Research

In the experiment, a higher precision Nokov optical motioncapture system (NOMCS) sensor is introduced and the AGVtrajectory from the NOMCS sensor is treated as a true refer-ence value in the comparison. The NOMCS platform is shownin Fig. 16, which contains 28 optical lenses. The NOMCSemits specific bands of infrared light through multiple infraredlenses arranged in space.

Citation Hao X, Yang H, Xu Y. Information fusion for positioning system with location constraint of camera and UWB[J]. IEEE Transactions on Automation Science and Engineering, 2025.

Link https://ieeexplore.ieee.org/document/11014219

Integrated Positioning System of Unmanned Automatic Vehicle in Coal Mines

Keywords

Extended Kalman filter (EKF), inertial navigation system (INS), odometer, ultra-wideband (UWB) positioning, underground coal mine.

Abstract

Automatic positioning technology of underground vehicles has become the key technology for the intelligent development of coal mines. To improve the comprehensive positioning accuracy of unmanned automatic vehicles in coal mines, an 18-D model of an odometer-aided inertial navigation system (INS) and a positioning model of an extended Kalman filter-based ultra-wideband (UWB) are established based on the vehicle kinematics equation. A tight integrated state estimation model is proposed to restrain the long-time drift of the INS and enhance the instability of the UWB system. A local positioning reference system based on an infrared motion capture system is established for the first time. Experimental tests show that the average positioning error of the proposed algorithm is 6.03 cm in the forward direction, and the root-mean-square error increased by 36.09% and 38.24% compared with those of the INS and UWB system, respectively. It is experimentally verified that the integrated positioning system achieves decimeter-level positioning accuracy in a coal mine roadway environment.

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Fig. 10. Field experimental layout of CUAV positioning system.

How NOKOV Contributes to the Research

To verify the actual positioning performance of the proposed method in an underground roadway, a laser inertial sensor (FOG INS300), a UWB positioning module (LinkTrack P), and an absolute odometer (CAS38R12E06R4B) were used to build the underground positioning experimental system. Particularly, the bias and noise of the gyroscope were 0.3° /h and 0.03°/√h, respectively, whereas those of the accelerometer were 0.07 mg and 0.013 mg√Hz, respectively. The experimental system coordinate frame was based on the UWB frame. The forward and right directions of the INS initial frame were aligned to the UWB frame using a laser rangefinder. The actual trajectory of the CUAV was captured by an IMCS comprising several infrared cameras (NOKOV Mars 2H). Time synchronization was realized through the time stamp information of the UWB system with the highest update frequency.

Citation Cui Y, Liu S, Yao J, et al. Integrated positioning system of unmanned automatic vehicle in coal mines[J]. IEEE Transactions on Instrumentation and Measurement, 2021, 70: 1-13.

Link https://ieeexplore.ieee.org/abstract/document/9440987

KD-EKF: A Consistent Cooperative Localization Estimator Based on Kalman Decomposition

Keywords

Location awareness; Jacobian matrices; Simultaneous localization and mapping; Monte Carlo methods; Filtering algorithms; Kalman filters; Observability; Cooperative localization; Kalman decomposition; Nonlinear estimation; Extended Kalman filter; Consisten

Abstract

In this paper, we revisit the inconsistency problem of EKF-based cooperative localization (CL) from the perspective of system decomposition. By transforming the linearized system used by the standard EKF into its Kalman observable canonical form, the observable and unobservable components of the system are separated. Consequently, the factors causing the dimension reduction of the unobservable subspace are explicitly isolated in the state propagation and measurement Jacobians of the Kalman observable canonical form. Motivated by these insights, we propose a new CL algorithm called KD-EKF which aims to enhance consistency. The key idea behind the KD-EKF algorithm involves perform state estimation in the transformed coordinates so as to eliminate the influencing factors of observability in the Kalman observable canonical form. As a result, the KD-EKF algorithm ensures correct observability properties and consistency. We extensively verify the effectiveness of the KD-EKF algorithm through both Monte Carlo simulations and real-world experiments. The results demonstrate that the KD-EKF outperforms state-of-the-art algorithms in terms of accuracy and consistency.

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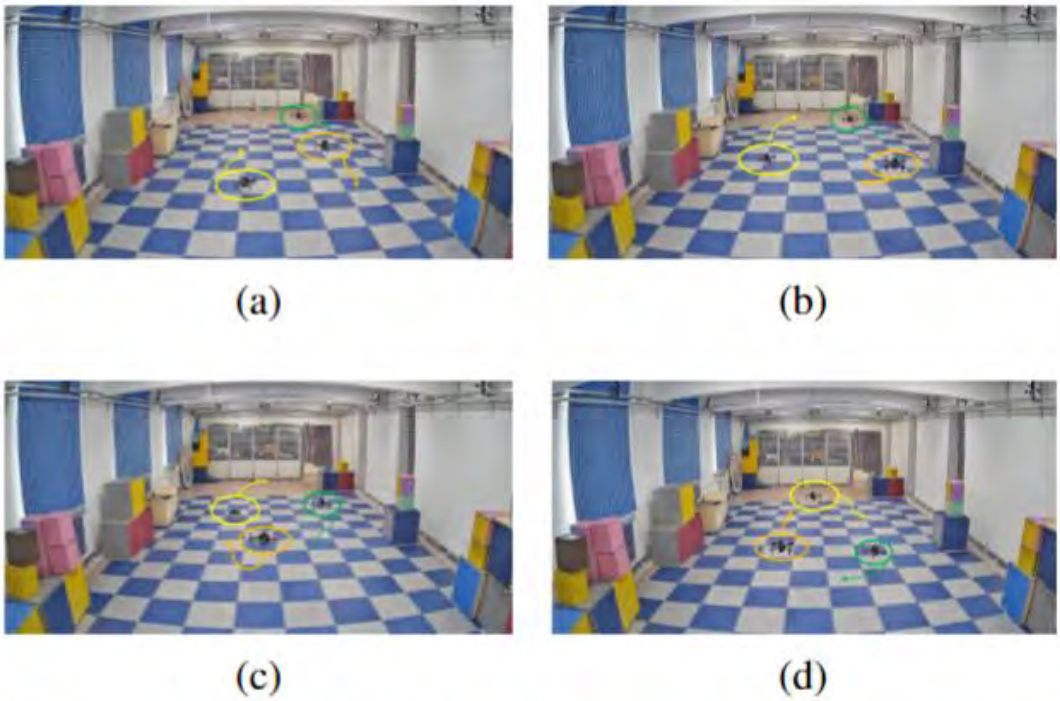

Fig. 4. Snapshots of the multi-robot system performing CL.

How NOKOV Contributes to the Research

To evaluate the localization results, we use the NOKOV motion capture system to track the poses of these robots as ground truth.

Citation N. Hao, F. He, C. Tian, Y. Yao and W. Xia, "KD-EKF: A Consistent Cooperative Localization Estimator Based on Kalman Decomposition," 2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Detroit, MI, USA, 2023, pp. 11064-11070, doi: 10.1109/IROS55552.2023.10341604.

Link https://ieeexplore.ieee.org/document/10341604

Landmark-aware autonomous odometry correction and map pruning for planetary rovers

Keywords

Planetary exploration, Unstructed environment, Saliency evaluation, Neural radiance fields, Visual odometry

Abstract

Planetary rover autonomous localization is paramount for a planetary surface exploration mission. However, existing methods demonstrate limited localization accuracy, mostly due to the unstructured texture characterization of planetary surface. In response, this study presents a novel Neural Radiance Field (NeRF) driven visual odometry correction method that allows for high-precision 6-DoF rover pose estimation and local map pruning. First, an innovative image saliency evaluation approach, combining binarization and feature detection, is introduced to meticulously select landmarks that are conducive to rover re-localization. Subsequently, we conduct 3D reconstruction and rendering of the chosen landmarks based on a-priori knowledge of planetary surface images and their Neural Radiance Field (NeRF) models. High-precision odometry correction is achieved through the optimization of photometric loss between NeRF rending images and real images. Simultaneously, the odometry correction mechanism is employed in an autonomous manner to refine the NeRF model of the corresponding landmark, leading to an improved local map and gradually enhanced rover localization accuracy. Numerical simulation and experiment trials are carried out to evaluate the performance of the proposed method, results of which demonstrate state-of-the-art rover re-localization accuracy and local map pruning.

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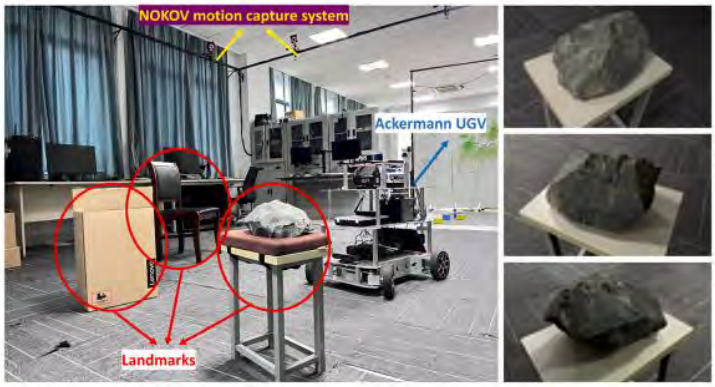

Fig. 12. (Left) The scene setup for experiment trial, with three landmarks set by us (a rock, a carton and a chair) marked in red, the NOKOV motion capture system marked in yellow, and the Ackermann UGV marked in blue. (Right) An example of NeRF rendering for the rock landmark in the scene.

How NOKOV Contributes to the Research

The pose estimate obtained by our method were compared with the ground truth acquired from the NOKOV motion capture system. The fraction of estimated poses with rotation and translation errors less than 2∘and 5 cm is depicted in Fig. 13.

Citation Lu C, Yu M, Li H, et al. Landmark-aware autonomous odometry correction and map pruning for planetary rovers[J]. Acta Astronautica, 2025, 226: 86-96.

Link https://webofscience.clarivate.cn/wos/alldb/full-record/WOS:001342285400001

Learning Real-Time Dynamic Responsive Gap-Traversing Policy for Quadrotors With Safety-Aware Exploration

Keywords

Quadrotors, Trajectory, Task analysis, Vehicle dynamics, Trajectory planning, Safety, Real-time systems

Abstract

In this paper, we propose a dynamic responsive policy for a quadrotor to traverse through narrow gaps based on deep reinforcement learning (RL). The policy provides agile and dynamically adjusted gap-traversing actions for the quadrotor in real-time by directly mapping the observed states of the quadrotor and gaps to motor thrusts. In contrast to existing optimization-based methods, our RL-based policy couples trajectory planning and control modules, which are strictly independent and computationally complex in previous works. Moreover, a safety-aware exploration is presented to reduce the collision risk and improve the safety of the policy, which also facilitates the transfer of the policy to real-world environments. Specifically, we formulate a safety reward on the state spaces of both position and orientation to inspire the quadrotor to traverse through the narrow gap at an appropriate attitude closer to the center of the gap. With the learned gap-traversing policy, we implement extensive simulations and real-world experiments to evaluate its performance and compare it with the related approaches. Our implementation includes several gap-traversing tasks with random positions and orientations, even if never trained specially before. All the performances indicate that our RL-based gap-traversing policy is transferable and more efficient in terms of real-time dynamic response, agility, time-consuming, and generalization.

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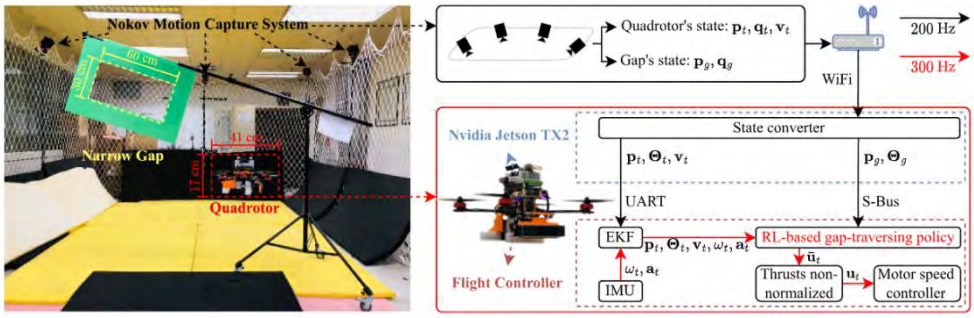

How NOKOV Contributes to the Research

The size of the narrow gap used in the experiments is 60 × 30 cm2, which indicates that the quadrotor can never safely traverse through the gap unless flying at a suitable tilted attitude. A Nokov motion capture system is used for the environmental perception, which outputs both the state information of the quadrotor and the gap at 200 Hz.

Citation S. Chen, Y. Li, Y. Lou, K. Lin and X. Wu, "Learning Real-Time Dynamic Responsive Gap-Traversing Policy for Quadrotors With Safety-Aware Exploration," in IEEE Transactions on Intelligent Vehicles, vol. 8, no. 3, pp. 2271-2284, March 2023, doi: 10.1109/TIV.2022.3229723.

Link https://ieeexplore.ieee.org/abstract/document/9991071

Learning Speed Adaptation for Flight in Clutter

Keywords

Aerial systems, applications, motion and path planning, reinforcement learning

Abstract

Animals learn to adapt speed of their movements to their capabilities and the environment they observe. Mobile robots should also demonstrate this ability to trade-off aggressiveness and safety for efficiently accomplishing tasks. The aim of this work is to endow flight vehicles with the ability of speed adaptation in prior unknown and partially observable cluttered environments. We propose a hierarchical learning and planning framework where we utilize both well-established methods of model-based trajectory generation and trial-and-error that comprehensively learns a policy to dynamically configure the speed constraint. Technically, we use online reinforcement learning to obtain the deployable policy. The statistical results in simulation demonstrate the advantages of our method over the constant speed constraint baselines and an alternative method in terms of flight efficiency and safety. In particular, the policy behaves perception awareness, which distinguish it from alternative approaches. By deploying the policy to hardware, we verify that these advantages can be brought to the real world.

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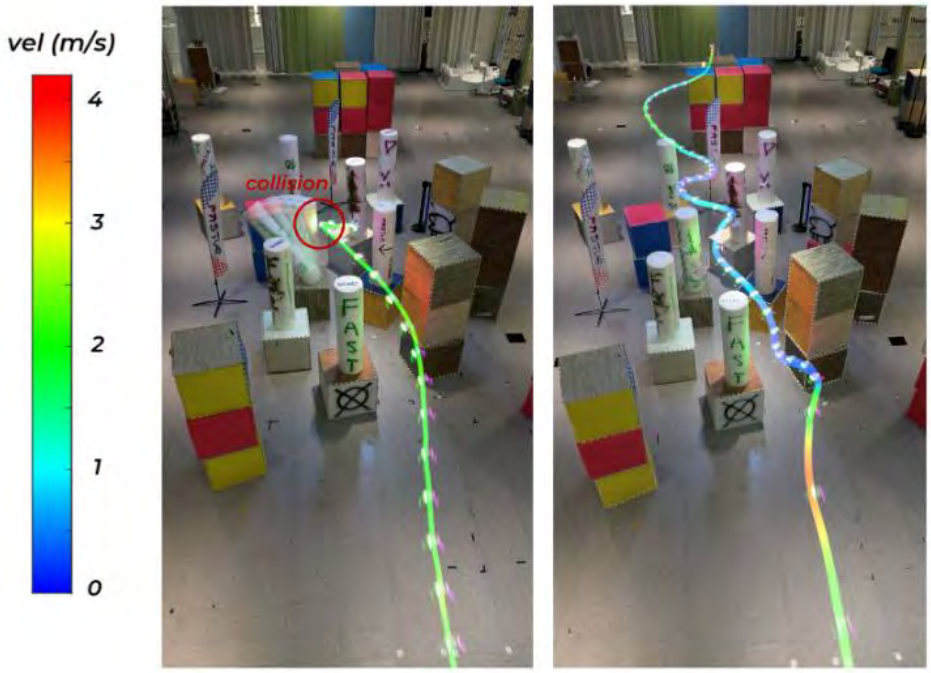

(a) (b)

How NOKOV Contributes to the Research

We deploy the policy on a micro drone with a size of 17 cm×17cm×10cm. The drone is equipped with an onboard Re-alSense D430 depth camera. Computation is performed on anonboard Jetson Orin NX module. We use the NOKOV motioncapture system and a VIO to obtain the state estimates in indoorand outdoor scenarios, respectively. The parameter setup isaligned with that in SectionVI-A.

Citation Zhao G, Wu T, Chen Y, et al. Learning speed adaptation for flight in clutter[J]. IEEE Robotics and Automation Letters, 2024, 9(8): 7222-7229.

Link https://ieeexplore.ieee.org/document/10582409

Learning-based Observer for Coupled Disturbance

Abstract

Achieving high-precision control for robotic systems is hindered by the low-fidelity dynamical model and external disturbances. Especially, the intricate coupling between internal uncertainties and external disturbances further exacerbates this challenge. This study introduces an effective and convergent algorithm enabling accurate estimation of the coupled disturbance via combining control and learning philosophies. Concretely, by resorting to Chebyshev series expansion, the coupled disturbance is firstly decomposed into an unknown parameter matrix and two known structures dependent on system state and external disturbance respectively. A regularized least squares algorithm is subsequently formalized to learn the parameter matrix using historical time-series data. Finally, a polynomial disturbance observer is specifically devised to achieve a high-precision estimation of the coupled disturbance by utilizing the learned portion. The proposed algorithm is evaluated through extensive simulations and real flight tests. We believe this work can offer a new pathway to integrate learning approaches into control frameworks for addressing longstanding challenges in robotic applications.

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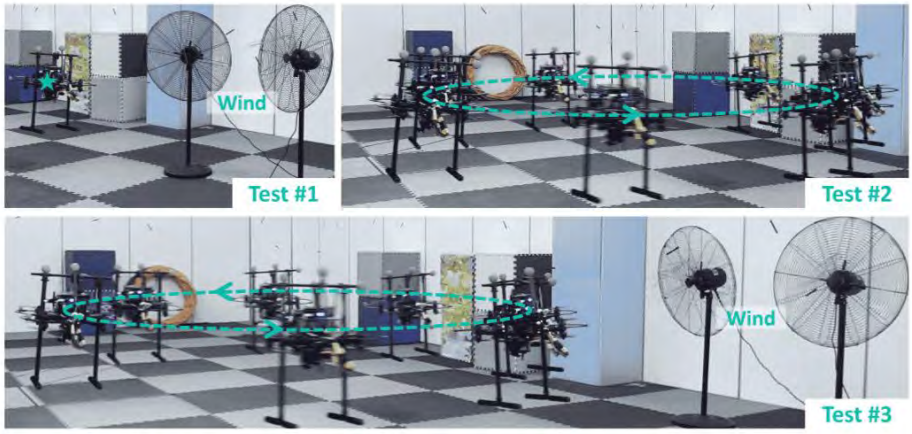

Fig. 4. Eexperimental scenarios in the drone example. The location state of the drone is provided by the NOKOV motion capture system. **A**, Hovering under wind disturbance. **B**, Circle flight under model uncertainty. **C**, Circle flight under model uncertainty and wind disturbance.

How NOKOV Contributes to the Research

Fig. 3.The tracking and estimation performance of the second-order dynamics example. A, The trajectory tracking performance. B, The disturbanceestimation performance. C, MAEs of all compared methods: NDO \[8], ESO \[6], \[33], L1adaptive \[5], \[34], EVOLVER \[35], the baseline controller(without compensation) and the proposed one (12).Fig. 4. Eexperimental scenarios in the drone example. The location state ofthe drone is provided by the NOKOV motion capture system. A, Hoveringunder wind disturbance. B, Circle flight under model uncertainty. C, Circleflight under model uncertainty and wind disturbance.

Citation Jia J, Wang M, Yang Z, et al. Learning-based Observer for Coupled Disturbance[J]. arXiv preprint arXiv:2407.13229, 2024.

Link https://arxiv.org/abs/2407.13229

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Learning-Based Passive Fault-Tolerant Control of a Quadrotor with Rotor Failure

Abstract

This paper proposes a learning-based passive fault-tolerant control (PFTC) method for quadrotor capable of handling arbitrary single-rotor failures, including conditions ranging from fault-free to complete rotor failure, without requiring any rotor fault information or controller switching. Unlike existing methods that treat rotor faults as disturbances and rely on a single controller for multiple fault scenarios, our approach introduces a novel Selector-Controller network structure. This architecture integrates fault detection module and the controller into a unified policy network, effectively combining the adaptability to multiple fault scenarios of PFTC with the superior control performance of active fault-tolerant control (AFTC). To optimize performance, the policy network is trained using a hybrid framework that synergizes reinforcement learning (RL), behavior cloning (BC), and supervised learning with fault information. Extensive simulations and real-world experiments validate the proposed method, demonstrating significant improvements in fault response speed and position tracking performance compared to state-of-the-art PFTC and AFTC approaches.

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Fig. 6. The quadrotor used in the real-world experiment.

How NOKOV Contributes to the Research

We validated our algorithm using a Q250 quadrotor frameequipped with T-MOTOR F60PRO motors paired with 5-inch propellers, capable of generating a maximum thrust of13Nper rotor. The relevant parameters of the quadrotorare summarized in Table I. The position and attitude ofthe quadrotor are observed using a NOKOV motion capturesystem Mars2H, which transmits data to the onboard com-puter (OrangePi) via WiFi at a frequency of 100 Hz. The onboard computer then relays this information to the PX4flight controller through MAVROS. The Extended KalmanFilter deployed on PX4 integrates the data to obtain reliableposition, velocity, and attitude estimates. Meanwhile, angularvelocity and linear acceleration are directly acquired fromthe onboard IMU. Fig. 6 presents the quadrotor diagram forreal-world experiments.

Citation J. Chen, K. Zhao, Z. Liu, Y. Li and Y. Lou, "Learning-Based Passive Fault-Tolerant Control of a Quadrotor with Rotor Failure," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 1876-1883, doi: 10.1109/IROS60139.2025.11245951.

Link https://ieeexplore.ieee.org/document/11245951

LF-3PM: a LiDAR-based Framework for Perception-aware Planning with Perturbation-induced Metric

Abstract

Just as humans can become disoriented in featureless deserts or thick fogs, not all environments are conducive to the Localization Accuracy and Stability (LAS) of autonomous robots. This paper introduces an efficient framework designed to enhance LiDAR-based LAS through strategic trajectory generation, known as Perception-aware Planning. Unlike vision-based frameworks, the LiDAR-based requires different considerations due to unique sensor attributes. Our approach focuses on two main aspects: firstly, assessing the impact of LiDAR observations on LAS. We introduce a perturbation-induced metric to provide a comprehensive and reliable evaluation of LiDAR observations. Secondly, we aim to improve motion planning efficiency. By creating a Static Observation Loss Map (SOLM) as an intermediary, we logically separate the time-intensive evaluation and motion planning phases, significantly boosting the planning process. In the experimental section, we demonstrate the effectiveness of the proposed metrics across various scenes and the feature of trajectories guided by different metrics. Ultimately, our framework is tested in a real-world scenario, enabling the robot to actively choose topologies and orientations preferable for localization. The source code is accessible at this https URL.The source code is accessible at https://github.com/ZJU-FAST-Lab/LF-3PM.

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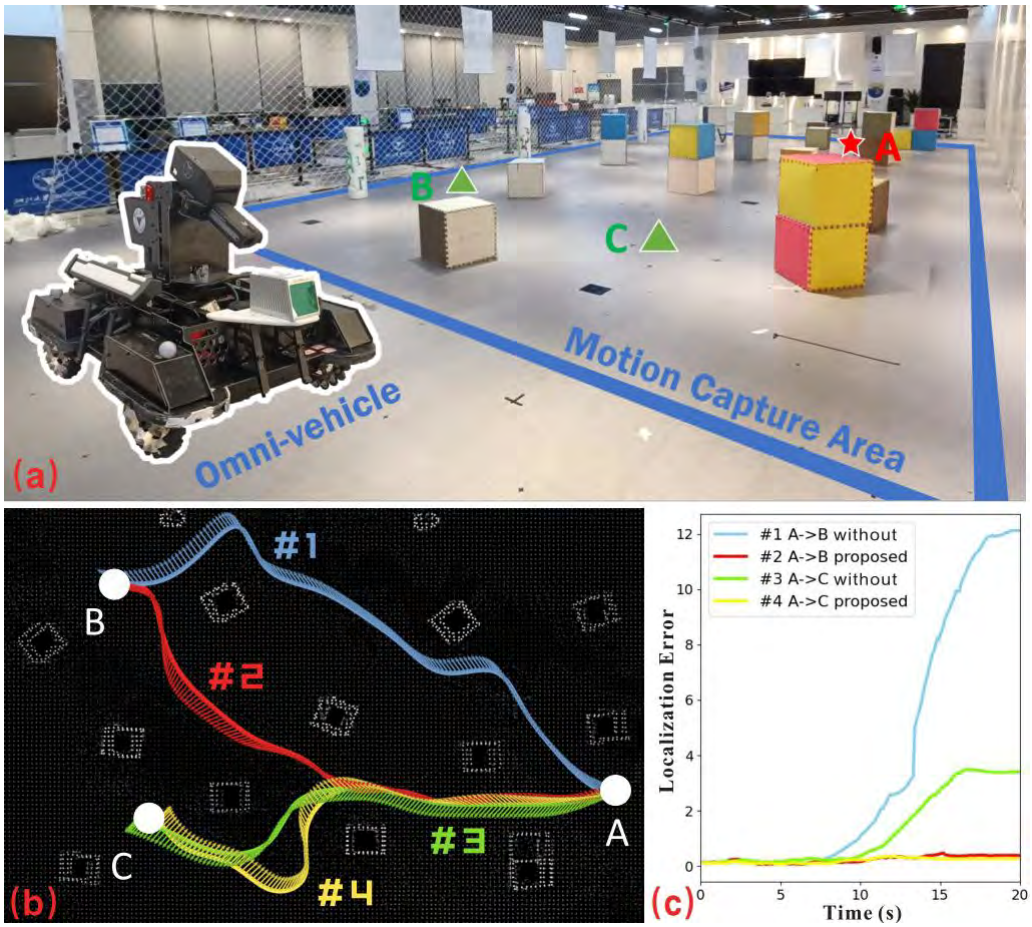

How NOKOV Contributes to the Research

The ground truth of robot pose is provided by the motion tracking system (NOKOV2).

Citation Chai K, Xu L, Wang Q, et al. LF-3PM: a LiDAR-based Framework for Perception-aware Planning with Perturbation-induced Metric[C]//2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2024: 5372-5379.

Link https://ieeexplore.ieee.org/abstract/document/10802556

Load Sharing in Distributed Collaborative Manipulation

Keywords

Distributed robot systems, robust/adaptive control, mobile manipulation

Abstract

The letter considers the multi-robot collaborative manipulation with load sharing characteristic, when dynamic parameters of the system composed of multiple robots and the rigid body are unknown. Load sharing refers to each robot calculating the required wrench for the manipulation task itself and actively sharing the manipulation duty when the global grasp matrix and system parameters are unknown. The global information however must be collected for the load distribution algorithm in the literature, where a central node is required for the distribution calculation. On the contrary, we propose a distributed control framework based on the idea of the weighted consensus and the parameter estimation to achieve the load sharing among robots according to the prescribed contribution factor, when only the local grasp matrix is needed. It is found that the manipulation wrench provided by the proposed controller causes no squeezing effect on the object at the steady state. The numerical simulation and real-robot experiments verify the effectiveness of the proposed framework.

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Fig. 7. Hardware of the collaborative manipulation system formed by three customized mecanum 4-wheeled robots.

How NOKOV Contributes to the Research

Each robot has a NUC (Intel 12th-generation mini PC) as the processing unit, which receives the states through the motion capture system (Nokov), runs the proposed control frame work and sends the resulting control signals to robots' STM32 micro-controllers to drive the 6-inch omnidirectional mecanum wheels through low-level PID controllers. The sampling frequencies of Nokov Mocap, proposed controller and low-level controllers are 100 Hz, 500 Hz and 1000 Hz, respectively.

Citation Du J, Liang Y, Tao H, et al. Load Sharing in Distributed Collaborative Manipulation[J]. IEEE Robotics and Automation Letters, 2025.

Link https://ieeexplore.ieee.org/document/10884853

M3DSS: A Multi-Platform, Multi-Sensor, and Multi-Scenario Dataset for SLAM System

Keywords

Event-based Dataset, SLAM, Multi-sensor, Multi-platform, Multi-scenario

Abstract

This paper proposed M3DSS, a multi-platform, multi-sensor, and multi-scenario dataset for Simultaneous Localization and Mapping (SLAM) systems. Fifty-five sequences were collected from multiple platforms, including a handheld equipment, an unmanned ground vehicle, a quadruped robot, a car, and an unmanned aerial vehicle. Sensors used in M3DSS included two pairs of stereo event cameras with resolutions of 640×480 and 346×260, one infrared camera, four RGB cameras, two visual-inertial sensors, four mechanical and one solid-state LiDARs, three inertial measurement units, two global navigation satellite and inertial navigation systems with real-time kinematic signals. 21 various sensors were used on 5 different platforms under various challenging scenarios, including extreme illumination, aggressive motion, low-texture, high-speed driving scenarios, etc. To the best of our knowledge, M3DSS offered the richest event-based sensory information for SLAM up to date. We comprehensively evaluated state-of-the-art SLAM approaches and identified their limitations on M3DSS. Details could be found at https://neufs-ma.github.io/M3DSS.

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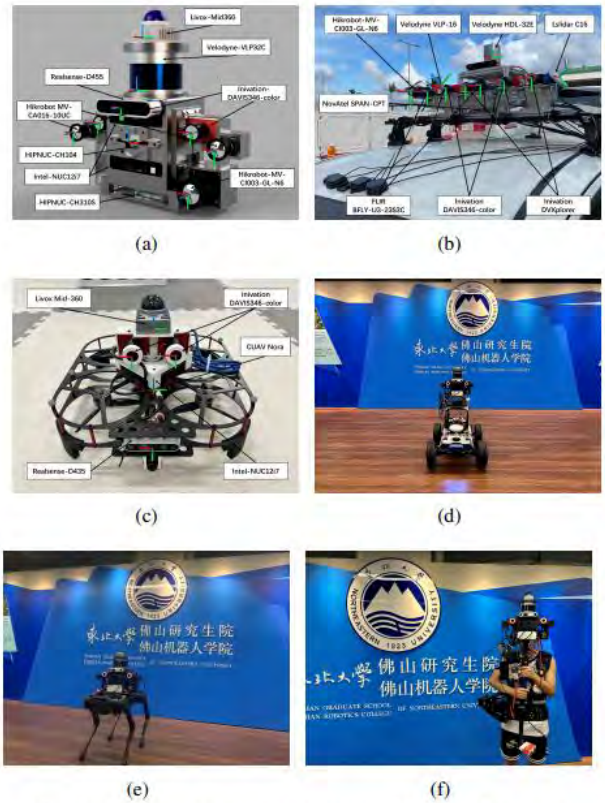

Fig. 1. (a) A multi-sensor device. (b) A multi-sensor device on a car. (c) A multi-sensor device on a UAV. (d) A UGV with the multi-sensor device. (e) A quadruped robot with the multi-sensor device. (f) a handheld device with the multi-sensor device. x-axis was red, y-axis was green, and z-axis was blue.

How NOKOV Contributes to the Research

For indoor scene with motion capture, we used a motion capture system NOKOV with 12 high-performance infrared motion capture cameras (240fps) to track the motion trajectory and motion information of the acquisition platform through reflective markers, thereby generating ground-truth.

Citation Huang S, Zhang H, Xu K, et al. M3DSS: A Multi-Platform, Multi-Sensor, and Multi-Scenario Dataset for SLAM System[C]//2025 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2025: 14542-14549.

Link https://ieeexplore.ieee.org/abstract/document/11128631

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Markerless Motion Capture for Humans Through a Multi-UAV System

Keywords

3σ rule based on re projection error, airborne cameras pose estimation, markerless motion capture, multi unmanned aerial vehicle (UAV) system, sparse point cloud reconstruction

Abstract

Capturing the motion of humans without any markers in a moving scene is a challenging issue. Typical methods, such as those based on fixed cameras or wearable sensors, have limits on the measurement range and the number of targets. Therefore, we propose a markerless motion-capture technique to estimate the 3-D pose of humans through a multi unmanned aerial vehicle (UAV) system. By utilizing the advantage of the large observation baselines between UAVs in the system, an algorithm to estimate the pose of airborne cameras and establish the sparse points cloud of background in overlapping view simultaneously was presented. A 3σ rule based on reprojection error is employed to eliminate the incorrect conjugate keypoint pairs, enhancing the precision of pose estimation for airborne cameras. To verify the accuracy of the developed technique, an indoor test was conducted to compare it with a commercial capture system, the results show that the average measurement error of the 3-D joints of humans is less than 30 mm. Furthermore, we demonstrate the feasibility of our approach in outdoor scenes, including multi-person scenarios and moving scenarios.

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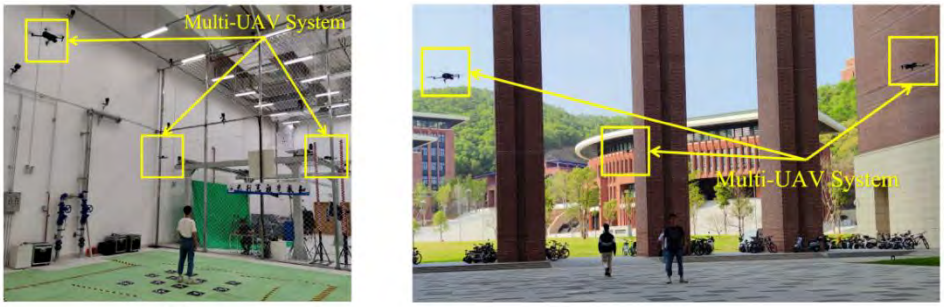

(a) (b)

Fig. 3. Experimental scenarios. (a) Indoor test. (b) Outdoor test.

How NOKOV Contributes to the Research

To verify the accuracy of the 3-D pose of people estimated through the presented method, a fixed camera-based motion-capture system named NOKOV was used to measure the position of joint points on the person in the indoor scene.It needs to install the reflective marker points on the surface of the joints, each joint has two centrally symmetrical reflective marker points, and the position of the joint point is calculated from two symmetrical reflective marker points.

Citation Zhuge S, He Y, Xu X, et al. Markerless motion capture for humans through a multi-UAV system[J]. IEEE Transactions on Instrumentation and Measurement, 2023, 73: 1-12.

Link https://ieeexplore.ieee.org/document/10339371

Merry-Go-Round: Safe Control of Decentralized Multi-Robot Systems with Deadlock Prevention

Abstract

We propose a hybrid approach for decentralized multi-robot navigation that ensures both safety and deadlock prevention. Building on a standard control formulation, we add a lightweight deadlock prevention mechanism by forming temporary "roundabouts" (circular reference paths). Each robot relies only on local, peer-to-peer communication and a controller for base collision avoidance; a roundabout is generated or joined on demand to avert deadlocks. Robots in the roundabout travel in one direction until an escape condition is met, allowing them to return to goal-oriented motion. Unlike classical decentralized methods that lack explicit deadlock resolution, our roundabout maneuver ensures system-wide forward progress while preserving safety constraints. Extensive simulations and physical robot experiments show that our method consistently outperforms or matches the success and arrival rates of other decentralized control approaches, particularly in cluttered or high-density scenarios, all with minimal centralized coordination.

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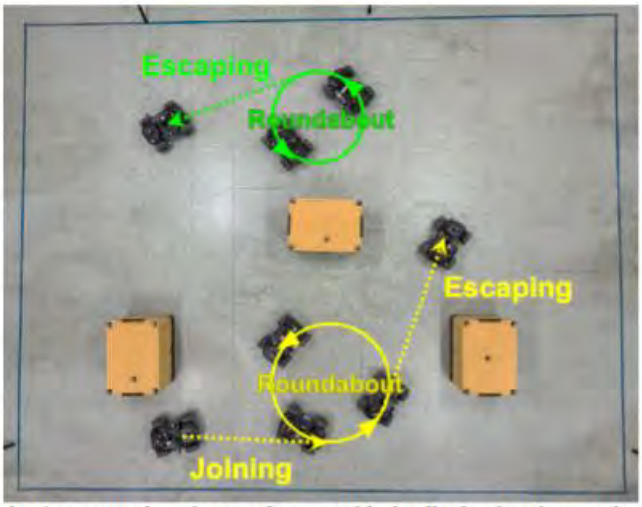

Fig. 1: An example where robots avoid deadlock situations using our proposed method — Merry-Go-Round. Robots encountering a potential deadlock form a roundabout and join it until they can escape to move ahead to their goal locations.

How NOKOV Contributes to the Research

We evaluate the proposed algorithm in simulations and also with physical robots. In all experiments, algorithms run on a laptop with an AMD Ryzen 7 5800 8-Core Processor and 32GB RAM, using CVXOPT as the quadratic programming solver. The physical robot experiment is done with DJI RoboMaster S1 robots where their states are measured using a motion capture system (six NOKOV Pluto 1.3C).

Citation W. Lee, J. Sim, J. Kim, S. Jo, W. Luo and C. Nam, "Merry-Go-Round: Safe Control of Decentralized Multi-Robot Systems with Deadlock Prevention," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 4589-4595, doi: 10.1109/IROS60139.2025.11245826.

Link https://ieeexplore.ieee.org/document/11245826

MERSYS: A Collaborative Estimation and Dense Mapping System for Multi-Agent Generic SLAM

Abstract

Multi-agent collaborative Simultaneous Localization and Mapping (SLAM) is an effective way for large-scale mapping. However, this approach, which relies on Visual-Inertial Odometry(VIO) as input, suffers from limitations such as susceptibility to environmental influences and the difficulty in accurately constructing dense 3D maps. To address these challenges, this paper presents Multi-Estimation Robust SLAM System (MERSYS), a novel framework for three-dimensional dense mapping based on the fusion of Lidar-Inertial Odometry(LIO) and VIO. Benefiting from lower communication's costs and dense information acquisition capability, the proposed framework aims to achieve compatibility in processing both LIO and VIO inputs, establish joint loop closure detection to enable multi-map fusion, and then create a comprehensive global 3D dense point cloud map. Furthermore, an efficient communication strategy has been proposed to enable bidirectional transmission of dense and voluminous data. Experimental evaluations conducted on the publicly available HILTI SLAM 2021 dataset[10] as well as a real world dataset. Experimental results show that MERSYS achieves better results than state-of-the-art methods. The source code is available on the GitHub1.

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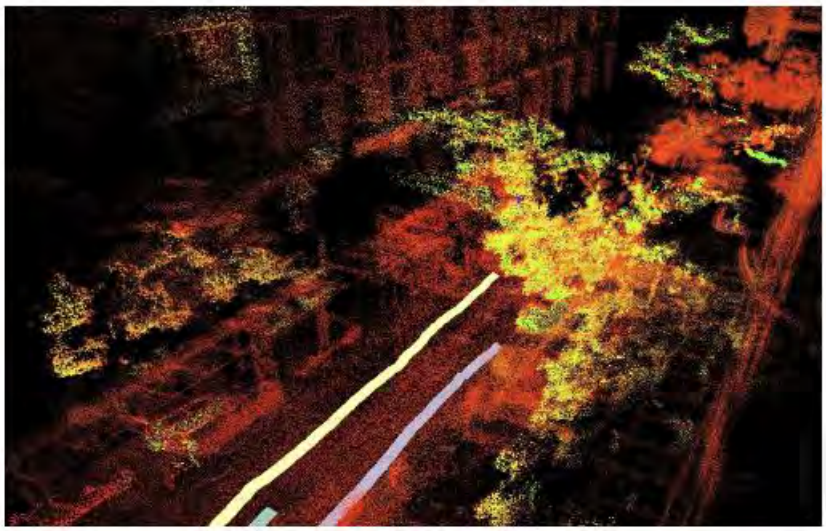

Fig. 1: We introduce MERSYS, a multi-agent SLAM framework compatible with both LIO and VIO.

How NOKOV Contributes to the Research

To capture ground truth data, we use RTK sensors for outdoor environments and the NOKOV motion capture system for indoor environments.

Citation Lai Q, Zhao E, Fan S, et al. MERSYS: A Collaborative Estimation and Dense Mapping System for Multi-Agent Generic SLAM[C]//2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2024: 5688-5695.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001411890000578

MineGPS: Battery-Free Localization Base Station for Coal Mine Environment

Keywords

Coal mine; robot self-positioning; battery-free,' base stations

Abstract

Rescue robot self-positioning is rescue. significant end, we propose a localization system with unique low-cost battery-free base stations for underground rescue robots, called MineGPS. The main idea is to design the battery-free base station with a unique arrangement sequence of reflective tags, and make robots identify each base station with computer vision-related technology to determine which base station it is near. In particular, inspired by Hamming code, we introduce a detection mechanism to correct the base station identification errors caused by dust covering in the mine. Finally, we present a robot localization algorithm by utilizing the location information of the base station. We implement MineGPS and evaluate its performance extensively. Results show that MineGPS can achieve the positioning accuracy with a median error of 15 cm. It is believed that MineGPS has a high potential to provide a low-cost and effective solution for the precise positioning of rescue robots in complex underground environments.

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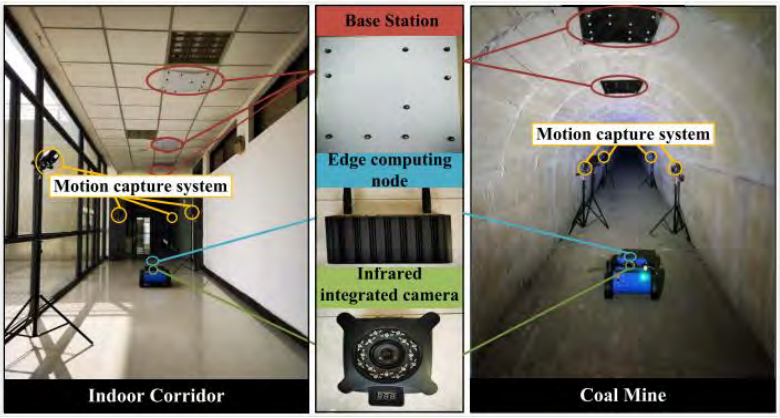

Fig. 8. Experimental scene.

How NOKOV Contributes to the Research

Furthermore, the motion capture system tracks the robot's actual position information in real-time. We conduct a thousand experiments under each experimental condition.

Citation Yang X, Yu X, Zhang C, et al. MineGPS: battery-free localization base station for coal mine environment[J]. IEEE communications letters, 2021, 25(8): 2579-2583.

Link

https://ieeexplore.ieee.org/search/searchresult.jsp?newsearch=true&queryText=MineGPS:%20Battery-Free%20Localization%20Base%20Station%20for%20Coal%20Mine%20Environment

Mixed-Integer and Conditional Trajectory Planning for an Autonomous Mining Truck in Loading/Dumping Scenarios: A Global Optimization Approach

Keywords

Abstract

Trajectory planning for a heavy-duty mining truck near the loading/dumping sites of an open-pit mine is difficult. As opposed to trajectory planning for a small-sized passenger car in a parking lot, trajectory planning for a heavy-duty mining truck involves complex factors in vehicle kinematics and environment. These factors make the concerned trajectory planning scheme a mixed-integer nonlinear program (MINLP) incorporated with conditional constraints (denoted as C-MINLP). MINLP solvers can neither deal with conditional constraints nor find global optima in real time. Instead of solving the C-MINLP directly, we build a from-coarse-to-fine framework so that the coupled difficulties (the mixed integral variables, conditional constraints, and the demand for global optimality) are divided and conquered. At the coarse search stage, a global-optimality-enhanced hybrid A search algorithm is proposed to find a near-optimal coarse trajectory with the mixed integral variables, conditional kinematic constraints, and global optimality considered. The coarse trajectory is further polished at the refinement stage, wherein the nominal C-MINLP is simplified as a small-scale NLP. The solution to the NLP is an optimized trajectory, which does not violate the complex constraints in the nominal C-MINLP. This indicates that conversion from the C-MINLP to an NLP is efficient with the help of a high-quality coarse trajectory.

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Fig. 7. An indoor workspace and a small-scale autonomous vehicle platform deployed for the field tests.

How NOKOV Contributes to the Research

Experiments were conducted on a small-size autonomous vehicle platform in a 1.75m 1.20m indoor workspace (Fig. 7). Six infrared sensors from the NOKOV Motion Capture System were deployed for obstacle perception and ego vehicle localization. Concretely, reflective marking points were placed on the surface of each stone-like obstacle and the top of the autonomous vehicle (Fig. 8). The infrared light sources would emit infrared beams, which are captured by the infrared sensors after being reflected by the marking points. Through this, the location of each marking point is identified.

Citation Li B, Ouyang Y, Li X, et al. Mixed-integer and conditional trajectory planning for an autonomous mining truck in loading/dumping scenarios: A global optimization approach[J]. IEEE Transactions on Intelligent Vehicles, 2022, 8(2): 1512-1522.

Link https://ieeexplore.ieee.org/document/9919391

MmWave Radar Perception Learning using Pervasive Visual-Inertial Supervision

Keywords

Scene flow, 4D mmWave radar, cross-modal learning, SLAM

Abstract

This article introduces a radar perception learning framework guided by data collected from commonly equipped visual-inertial (VI) sensor suites on smart vehicles. Unlike existing approaches that rely on dense point clouds from 3D LiDARs, which are costly and not widely deployed, this method leverages the broader availability of VI data. However, visual images alone lack the ability to capture the three-dimensional motion of moving targets, which limits their effectiveness in supervising motion-related tasks. To overcome this limitation, the framework integrates multiple perception tasks such as odometry estimation, motion segmentation, and scene flow prediction into a unified learning process. The first component is an odometry estimation module that combines deterministic ego-motion models with data-driven learning results. This fusion helps accurately infer the scene flow of static background points while minimizing drift. The second component is a supervision signal extraction module that aligns optical and millimeter-wave radar measurements to guide the learning of radar scene flow and rigid transformations. This module improves the reliability of dynamic point supervision through joint constraints across sensing modalities. The third component introduces a feature-selection module designed for cross-modal learning. It enhances the accuracy of motion segmentation and enforces consistency between odometry and scene flow, resulting in more coherent radar perception outputs. Experimental evaluations show that this framework achieves superior performance in challenging conditions such as smoke-obscured environments. It surpasses state-of-the-art (SOTA) methods that depend on high-cost LiDAR systems.

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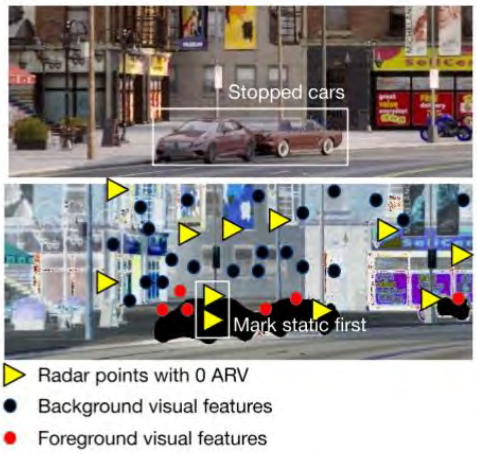

Fig. 5. Leveraging background visual features to find more background radar points.

How NOKOV Contributes to the Research

C. Ground Truth LabelingAlthough VISC+is designed for self-supervised learningand does not rely on ground truth during training, annotatedlabels are still necessary for performance evaluation. Follow-ing the protocol in \[32], we generate ground truth scene flowusing object detection results (i.e., bounding boxes) alongwith accurate radar odometry. For the indoor dataset, groundtruth odometry is obtained using the NOKOV motion capture system, which provides high-precision pose information. Inoutdoor environments, we utilize VINS-Fusion1to integrateRGB images, IMU data, and GPS signals for producingreliable odometry estimates. For static background points, theircorresponding scene flow vectors are labeled based on theradar's ground truth motion.

Citation Liu K, Zhou Y, Chen M, et al. mmWave Radar Perception Learning Using Pervasive Visual-Inertial Supervision[J]. IEEE Transactions on Intelligent Transportation Systems, 2026.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001691193500001

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Model Predictive Control of a Novel Wheeled–Legged Planetary Rover for Trajectory Tracking

Keywords

mobile robot; advanced intelligent control; wheeled–legged; trajectory tracking; model predictive control;

Abstract

Amid increasing demands for planetary exploration, wide-range autonomous exploration is still a great challenge for existing planetary rovers, which calls for new planetary rovers with novel locomotive mechanisms and corresponding control strategies. This paper proposes a novel wheeled–legged mechanism for the design of planetary rovers. The leg suspension utilizes a rigid–flexible coupling mechanism with a hybrid serial–parallel topology. First, the kinematic model is derived. Then, a control strategy for the wheeled–legged rover that includes a trajectory tracking module based on the model predictive control, the steering strategy, and the wheel speed allocation algorithm is proposed. After that, three groups of cosimulations with different trajectories and speeds, and experiments are carried out. Results of both the simulations and experiments validate the proposed control method.

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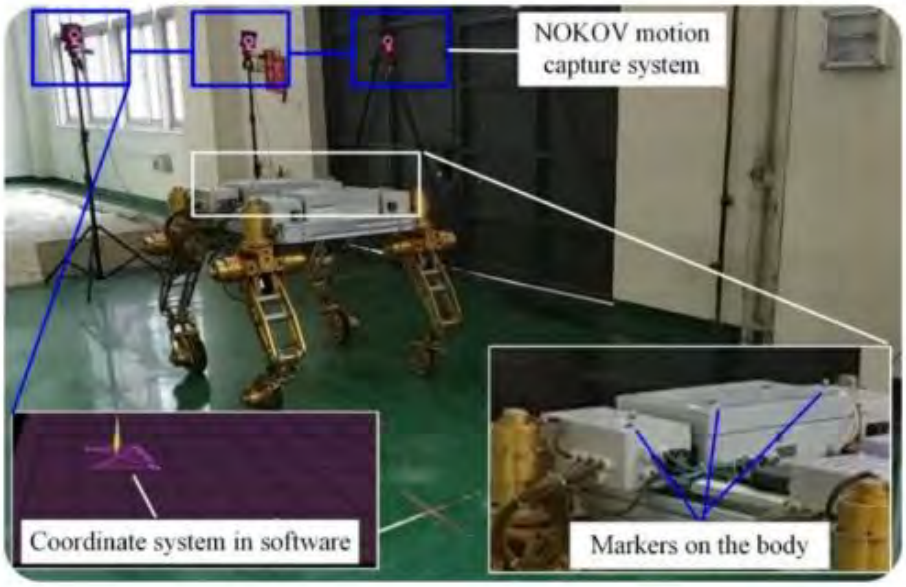

Figure 16. The experimental setup.

How NOKOV Contributes to the Research

To further verify the control strategy, an experimental setup based on the NOKOV vision motion capture system was established that consisted of six cameras, as shown in Figure 16.

Citation He J, Sun Y, Yang L, et al. Model predictive control of a novel wheeled–legged planetary rover for trajectory tracking[J]. Sensors, 2022, 22(11): 4164.

Link https://www.mdpi.com/1424-8220/22/11/4164

Model-Based Planning and Control for Terrestrial-Aerial Bimodal Vehicles with Passive Wheels

Keywords

Trajectory tracking, Computational modeling, Dynamics, Wheels, Benchmark testing, Predictive models, Planning

Abstract

Terrestrial and aerial bimodal vehicles have gained widespread attention due to their cross-domain maneuverability. Nevertheless, their bimodal dynamics significantly increase the complexity of motion planning and control, thus hindering robust and efficient autonomous navigation in unknown environments. To resolve this issue, we develop a model-based planning and control framework for terrestrial aerial bi-modal vehicles. This work begins by deriving a unified dynamic model and the corresponding differential flatness. Leveraging differential flatness, an optimization-based trajectory planner is proposed, which takes into account both solution quality and computational efficiency. Moreover, we design a tracking controller using nonlinear model predictive control based on the proposed unified dynamic model to achieve accurate trajectory tracking and smooth mode transition. We validate our framework through extensive benchmark comparisons and experiments, demonstrating its effectiveness in terms of planning quality and control performance.

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How NOKOV Contributes to the Research

To demonstrate and verify the proposed approaches in real-world environments, we customize a TABV platform, as shown in Fig.4. The corresponding physical parameters are listed in Tab.I. The 6D localization of the TABV and the environmental information are obtained from a NOKOV motion capture system1 and a Realsense D430 stereo camera, respectively.

Citation R. Zhang et al., "Model-Based Planning and Control for Terrestrial-Aerial Bimodal Vehicles with Passive Wheels," 2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Detroit, MI, USA, 2023, pp. 1070-1077, doi: 10.1109/IROS55552.2023.10342188.

Link https://ieeexplore.ieee.org/document/10342188

MOGS: Monocular Object-guided Gaussian Splatting in Large Scenes

Abstract

Recent advances in 3D Gaussian Splatting (3DGS) deliver striking photorealism, and extending it to large scenes opens new opportunities for semantic reasoning and prediction in applications such as autonomous driving. Today's state-of-the-art systems for large scenes primarily originate from LiDAR-based pipelines that utilize long-range depth sensing. However, they require costly high-channel sensors whose dense point clouds strain memory and computation, limiting scalability, fleet deployment, and optimization speed. We present MOGS, a monocular 3DGS framework that replaces active LiDAR depth with object-anchored, metrized dense depth derived from sparse visual-inertial (VI) structure-from-motion (SfM) cues. Our key idea is to exploit image semantics to hypothesize per-object shape priors, anchor them with sparse but metrically reliable SfM points, and propagate the resulting metric constraints across each object to produce dense depth. To address two key challenges, i.e., insufficient SfM coverage within objects and cross-object geometric inconsistency, MOGS introduces 1) a multi-scale shape consensus module that adaptively merges small segments into coarse objects best supported by SfM and fits them with parametric shape models, and 2) a cross-object depth refinement module that optimizes per-pixel depth under a combinatorial objective combining geometric consistency, prior anchoring, and edge-aware smoothness. Experiments on public datasets show that, with a low-cost VI sensor suite, MOGS reduces training time by up to 30.4% and memory consumption by 19.8%, while achieving high-quality rendering competitive with costly LiDAR-based approaches in large scenes.

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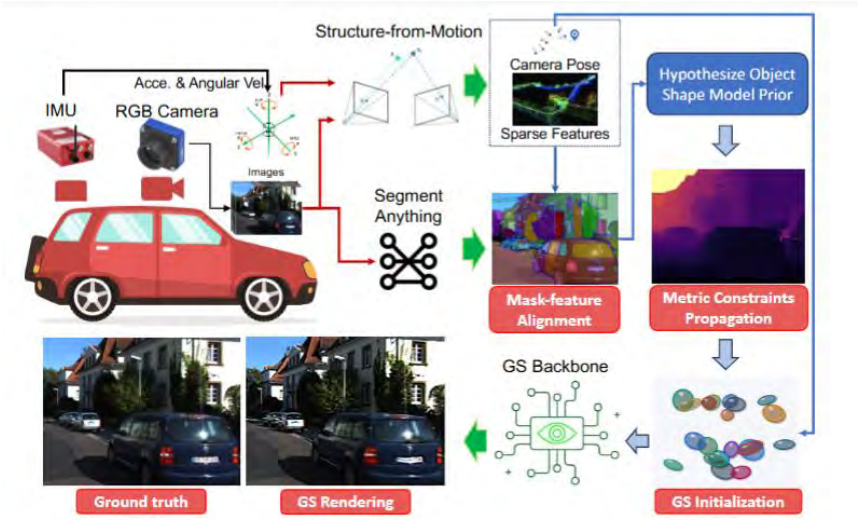

Fig. 1: MOGS exploits the rich semantics of RGB images and sparse, metrically reliable SfM cues to infer object-level shape priors. By propagating these metric constraints through shape priors, it produces metrized dense depth, approaching the effect of costly high-channel LiDAR, thereby enabling better Gaussian initialization and higher-quality rendering.

How NOKOV Contributes to the Research

Datasets and Metrics. We use KITTI-Depth [31] collection that covers urban, residential, road, and campus traffic scenes. The raw sensor platform comprises two global-shutter stereo rigs, a Velodyne HDL-64E LiDAR, and an OXTS RT3003 high-precision IMU; cameras and LiDAR are synchronized at 10 Hz, and the IMU at 100 Hz. KITTI-Depth provides approximately 93 k semi-dense depth maps temporally aligned with RGB camera and LiDAR. In addition, we also use KITTI-360 [32] that contains large-scale suburban cruising (total distance 73.7 km, over 83 k frames). The platform carries a forward-looking perspective stereo pair plus fisheye cameras, a Velodyne LiDAR, and SICK push-broom 2D lasers, providing 360° perception with consistent semantic labels. Ground-truth camera poses are retrieved from the datasets or captured via a motion capture system like NOKOV using customized experimental platforms. Correspondingly, all ground-truth depth maps were temporally and spatially aligned with the captured images.

Monocular Visual SLAM based on VGG Feature Point Extraction

Keywords

monocular, visual SLAM, feature point extraction, convolutional neural network

Abstract

Significant progress has been made in the field of visual SLAM (Simultaneous Localization and Mapping). However, the localization accuracy of visual SLAM can be significantly reduced in low-texture and illumination-changing environments. To solve these problems, an enhanced visual SLAM algorithm based on VGG (Visual Geometry Group) network was proposed in this paper. Firstly, the VGG network for feature point extraction was incorporated into the visual odometry (VO) to achieve robust camera pose estimation. Secondly, an automatic corner annotation method was adopted to set up the training database, which could reduce the workload of data annotation. Thirdly, to make the backend optimization more suitable for the VGG based VO, the BA (bundle adjustment) optimization process was improved. Experimental results showed that, the proposed visual SLAM method outperformed the mainstream ORB-SLAM (Oriented FAST and Rotated BRIEF SLAM) method, in terms of the number of effective feature points, the robustness of feature matching process to light changes, and the accuracy of robot pose estimation.

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Fig. 11: Motion capture system produced by NOKOV Company. The system consists of several cameras and a ground station. With the software on the ground station, it can provide the pose of a prescribed rigid captured by the cameras.

How NOKOV Contributes to the Research

Motion capture system produced by NOKOV Company. The system consists of several cameras and a ground station. With the software on the ground station, it can provide the pose of a prescribed rigid captured by the cameras.

Citation Dai X Y, Meng Q H, Zheng W J, et al. Monocular Visual SLAM based on VGG Feature Point Extraction[C]//2020 39th Chinese Control Conference (CCC). IEEE, 2020: 3375-3380.

Link https://ieeexplore.ieee.org/abstract/document/9188606

MTABot: An Efficient Morphable Terrestrial-Aerial Robot With Two Transformable Wheels

Keywords

Aerial systems: Mechanics and control, mechanism design, multimodal locomotion, terrestrial-aerial robot

Abstract

Terrestrial-aerial robots, capable of swift aerial navigation and enduring terrestrial operations, possess significant potential for utilization in exploration and rescue missions. However, achieving their capability to negotiate diverse terrains with a high-power-efficient structure remains a formidable challenge. This letter presents a morphable terrestrial-aerial robot, named MTABot, which achieves three modalities through the deployment of two multifunctional appendages. These include: 1) rolling mode, 2) climbing mode, both achieved with transformable two-wheeled configuration, and 3) flying mode, achieved with a bicopter configuration. Moreover, the radius and sector angle of transformable wheel have been optimized to enhance the obstacle-climbing capability; the position of the robot's body center of gravity has been optimized to balance ground gripping capacity and flight dynamic response speed. Finally, the robot's multi-terrain overcoming capability is validated through obstacle-climbing experiments and continuous terrestrial-aerial transformation experiments, and the high power efficiency of robot is affirmed, demonstrating feasibility of the design.

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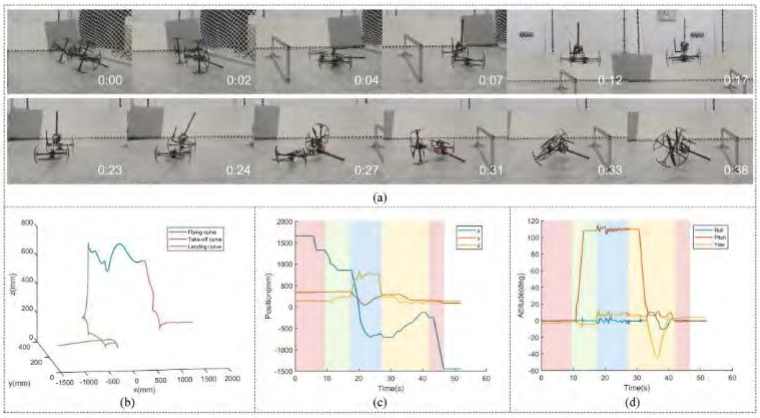

Fig. 10. Terrestrial-aerial transformation result. (a) Time sequence of terrestrial-aerial transformation. (b) 3D trajectory points corresponding to (a). (c) Position response corresponding to (a). (d) Attitude response corresponding to (a).

How NOKOV Contributes to the Research

The experiment took place indoors, using the NOKOV motion capture system at a 60Hz sampling frequency for data collection.

Citation K. Shi, Z. Jiang, L. Ma, L. Qi and M. Jin, "MTABot: An Efficient Morphable Terrestrial-Aerial Robot With Two Transformable Wheels," in IEEE Robotics and Automation Letters, vol. 9, no. 2, pp. 1875-1882, Feb. 2024, doi: 10.1109/LRA.2024.3349962.

Link https://ieeexplore.ieee.org/document/10380664

Multi-Agent Visual-Inertial Localization forIntegrated Aerial Systems With LooseFusion of Odometry and Kinematics

Keywords

Aerial Systems: applications, localization, multi-robot SLAM

Abstract

Reliably and efficiently estimating the relative pose and global localization of robots in a common reference for Integrated Aerial Platforms (IAPs) is a challenging problem. Unlike unmanned aerial vehicle (UAV) swarms, where the agent individual is able to move freely, IAPs connect UAV agents with mechanical joints, such as spherical joints, and form a rigid central platform, limiting the degree of freedom (DOF) of agents. Traditional methods, which rely on forming loop closures, object detection, or range sensors, suffer from degeneration or inefficiency due to the restricted relative motion between agents. In this paper, we present a centralized multi-agent localization system that fuses the internal kinematic constraints of IAPs and odometry measurements, using only visual-inertial suits for ego-motion estimation for agents and an additional 9-DOF Inertial Measurement Unit (IMU) attached to the central platform for posture estimation. A general formulation for kinematic constraints is derived without requiring knowledge about detailed kinematic parameters. A sliding-window optimization-based state estimator is constructed to estimate the relative transformation between agents. Our proposed approach is validated in our collected dataset. The results show that the proposed method reduces the global localization drift by 27.15% and relative localization error by 53.4% in the translation part and 36.99% in the rotation part compared to the baseline.

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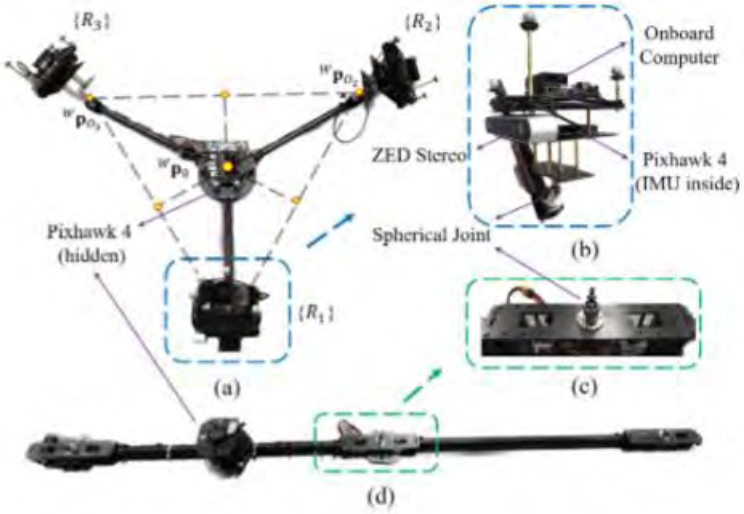

Fig. 4. Experiment platforms.

How NOKOV Contributes to the Research

The NOKOV motion capture system is utilized to provide the ground truth pose. Our dataset includes 7 sequences where sequences 1-5 are for the IAP, and sequences 6 and 7 are for the LIAP. A snapshot of the dataset appears in Fig. 5, and the trajectory length and duration are detailed in Table I. More details are presented in the attached video.

Citation Lai, G., Shi, C., Wang, K., Yu, Y., Dong, Y., & Franchi, A. (2024). Multi-agent visual-inertial localization for integrated aerial systems with loose fusion of odometry and kinematics. IEEE Robotics and Automation Letters, 9(7), 6504-6511.

Link https://ieeexplore.ieee.org/document/10542321/

Multiplayer Obstacle Avoidance Pursuit-EvasionGames With Adaptive Parameter Estimation

Keywords

Adaptive estimation, multiplayer pursuit-evasion (MPPE) game, obstacle avoidance, topology graph

Abstract

This article investigates a class of multiplayer obstacle avoidance pursuit-evasion games with intracoalition cooperation and intercoalition confrontation. In order to obtain distributed control strategy, a communication topology graph is utilized to quantify the interactions of the players. The solutions of the Hamilton–Jacobi–Isaacs equations of the pursuit-evasion games are employed to calculate Nash equilibrium of the players. An adaptive method is utilized to obtain the opponent's control parameters for updating multiple distributed control strategies. Moreover, the sufficient condition is provided to guarantee stability of multiplayer pursuit-evasion (MPPE) game system with adaptive estimation. Finally, an MPPE game experiment with two evaders and two pursuers is carried out to demonstrate the effectiveness of the proposed methodology.

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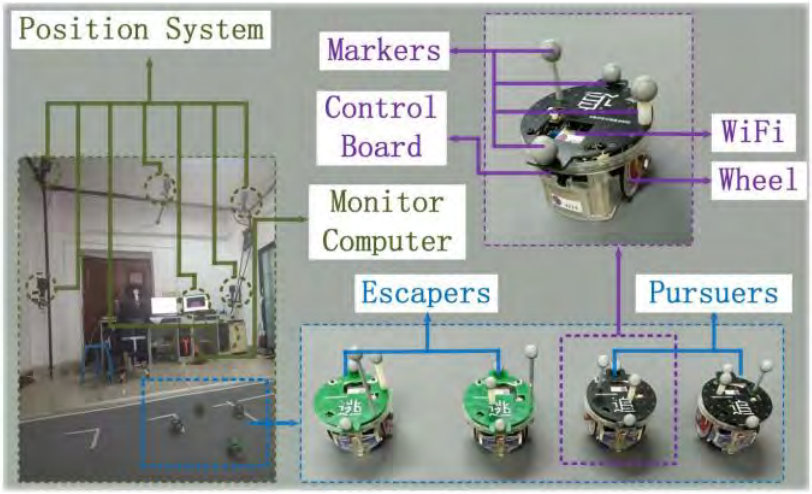

Fig. 2. MPPE game wheeled mobile robots platform.

How NOKOV Contributes to the Research

In this section, a group of experiments are presented to demonstrate the effectiveness of the proposed methodology. As shown in Fig. 2, the MPPE game wheeled mobile robots platform consists of an optical 3-D motion capture positioning system (Nokov, Mars 2H) with 12 cameras (2.2 mega pixels, 380 Hz frame rate, 2048×1088 image resolution, 2.4 ms delay), a monitor computer (Lenovo Savior Blade 7000), and four wheeled mobile robots (E-puck2).

Citation Cheng L, Yuan Y. Multiplayer obstacle avoidance pursuit-evasion games with adaptive parameter estimation[J]. IEEE Transactions on Industrial Electronics, 2022, 70(5): 5171-5181.

Link https://ieeexplore.ieee.org/abstract/document/9819436

Multi-Player Pursuit-Evasion Game With Interaction Constraints: A Cooperative Game Theoretic Approach Based on Coalition Structure

Keywords

Pursuit-evasion, differential game, cooperation-competition, obstacle avoidance, coalition structure

Abstract

This paper presents a comprehensive mathematical approach to address the multi-player and multi-objective pursuit-evasion games problem, incorporating coalition structure constraints from a cooperation-competition perspective. Social interaction networks are developed to approximate priority communication alliances based on individual References, establishing a multi-connected topology and decision space for the games. An N-player variable-sum differential game model, featuring autonomous obstacle avoidance, is formulated by integrating kinematic constraints and the social forces method. Rigorous proofs are provided for the uniqueness of payoff distribution, the stability of alliance structures, and the convergence of many-to-many differential games to Nash Equilibrium. Simulation and experimental results are presented to validate the effectiveness and performance of the proposed method. Note to Practitioners—A structured stable alliance is essential for fostering collective intelligence, especially in scenarios marked by intense conflict and the necessity for cooperation. While traditional methods (e.g., optimal control, differential games) are widely studied, many rely on rigid, random, or preassigned large-scale alliances that miss dynamic group interactions and cooperative alliance dynamics, leading to inefficient resource allocation. Drawing inspiration from social force models, we propose a novel coalition-structure-based cooperative game theory framework. By integrating multi-agent interactions via a coupled differential game on interconnected topologies, it offers new perspectives for multi-agent pursuit-evasion with obstacles and coalition constraints, advancing collective intelligence research in military defense, law enforcement, and maritime surveillance — domains where group dynamics are critical.

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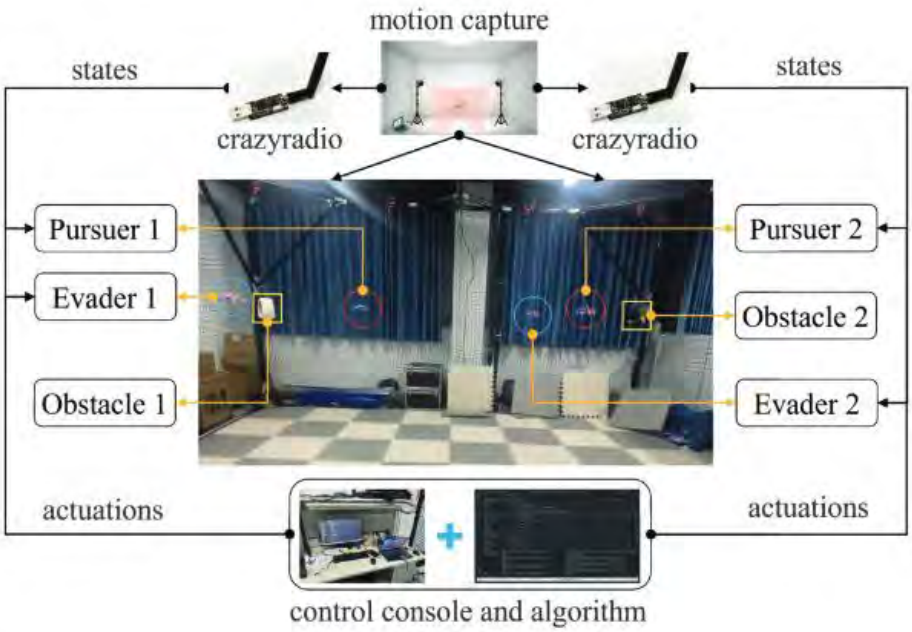

Fig. 10. Framework and conceptual diagram of the experimental setup.

How NOKOV Contributes to the Research

The system, employing Python, CRTP protocol, multi-threading, and swarm functions, demonstrated dynamicconstraint robustness. Key parameters: 100-s task horizon with 15 fps trajectory monitoring, 1.2-m drone altitude,0.1m × 1.2m obstacles. Critical thresholds: 30-cm intra-coalition separation for collision avoidance, 40-cm capture radius. Hardware: 4 Crazyflie 2.1 drones with NOKOV optical motion capture and 2.4 GHz Crazyradio PA communication.

Citation Ma X, Lv M, Duan K, et al. Multi-Player Pursuit-Evasion Game with Interaction Constraints: A Cooperative Game Theoretic Approach Based on Coalition Structure[J]. IEEE Transactions on Automation Science and Engineering, 2025.

Link https://ieeexplore.ieee.org/document/11045714

Multi-Robot Object Transport Motion Planning With a Deformable Sheet

Keywords

Multi-robot manipulation; Path planning for multiple mobile robots

Abstract

Using a deformable sheet to handle objects is convenient and found in many practical applications. Modeling of deformable sheet-object interactions and robot formation are among the main challenges in multi-robot object manipulation through deformable sheets. Motion planning of robotic team is critical for object manipulation quality. We present a computational robots-sheet-object model and the dual-capability robotic motion planner for optimal trajectory. A computational virtual variable cables model (VVCM) is presented to simplify the modeling of the deformable sheet with an arbitrary number of used robots. The motion planner is first formulated as a formation optimization problem. A path generation algorithm is then employed for obstacle avoidance and crossing features. The motion planner successfully produces an obstacle crossing path in complex scenarios where other benchmark planners fail. The effectiveness and versatility of the motion planner are verified and demonstrated by a robotic team of three robots. We further extend the results to a larger number of robots to illustrate the algorithms and analysis.

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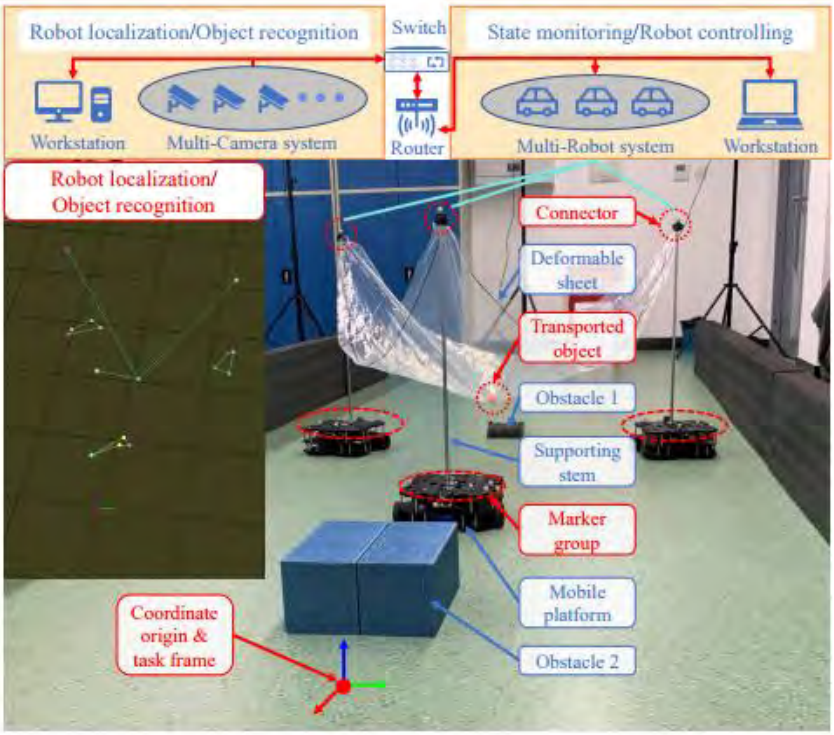

Fig. 6. Experimental setup and communication network of the multi-mobile robot transportation system.

How NOKOV Contributes to the Research

The position of robots and object were acquired at a rate of 60 Hz by the NOKOV motion capture system with 8 cameras.

Citation Hu J, Liu W, Zhang H, et al. Multi-robot object transport motion planning with a deformable sheet[J]. IEEE Robotics and Automation Letters, 2022, 7(4): 9350-9357.

Link https://ieeexplore.ieee.org/document/9830876

Multi-rotor UAV path planning based on Model Predictive Control and Control Barrier Function

Keywords

model predictive control, control barrier function, path planning

Abstract

The safety of unmanned aerial vehicles (UAVs) path planning in autonomous urban flight is challenging due to the presence of buildings. Previous studies have focused more on the distance between buildings and UAVs, but ignored the effect of UAV state on path planning. In this paper, we propose a path planning method based on model predictive control (MPC) and control barrier functions (CBF) for UAVs to effectively address the challenge of autonomous UAVs flight. By incorporating CBF and MPC, the MPC optimization is formulated to predict the UAV's flight path based on the current state of the UAV in the receding horizon before considering obstacle avoidance. The CBF constraint guarantees that there are no collisions between the UAV and obstacles, and that the MPC creates an optimal path. This method helps planners design control strategies that meet safety requirements. It improves the spatial configuration between the UAV and nearby obstacles, ensuring that they remain outside the safe range. The method has been verified through simulation and real-world experiments, demonstrating that the UAV maintains a safe distance from obstacles and can also find the shortest path during its flight.

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Fig. 5. Real-world path planning and obstacle avoidance scenarios.

How NOKOV Contributes to the Research

The real-world experiment uses the Mars 1.3H motioncapture camera from Nokovto capture the position, velocity,acceleration, and obstacle location of the UAV indoors. TheMars 1.3H motion capture camera has a high pixel count of13 million, a high frame rate of 240FPS, and a low latency of 4ms, which can provide highly accurate information about the UAV's position and attitude.

Citation Li S, Chen Y, Yang Y. Multi-rotor UAV path planning based on Model Predictive Control and Control Barrier Function[C]//2024 36th Chinese Control and Decision Conference (CCDC). IEEE, 2024: 1141-1146.

Link https://ieeexplore.ieee.org/abstract/document/10587478

Multiscale Variational Autoencoder Aided Convolutional Neural Network for Pose Estimation of Tunneling Machine Using A Single Monocular Image

Keywords

Pose estimation, convolutional neural network, variational autoencoder, computer vision, tunnelling.

Abstract

With the rising demand of underground construction, intelligent tunneling techniques have been increasingly studied to improve the safety and efficiency of construction. The self-positioning technology of tunneling machines is the cornerstone of intelligent tunneling, which is particularly challenging due to the extreme environments of the underground tunnels. In this paper, a novel robust and real-time six degrees of freedom (6-DoF) pose estimation strategy is proposed for tunneling machines based on the computer vision and deep learning methods. A monocular camera is attached to the tunneling machine, and employed to capture the images of the artificial feature object that is set far behind the tunneling machine. A novel multi-scale variational autoencoder aided convolutional neural network (MSVAE-CNN) model is developed to estimate the current absolute 6-DoF pose of the tunneling machine in an end-to-end manner using a single monocular image, in which the multi-task variational learning scheme is able to enhance the generalization and robustness of the model and the multi-scale structure can improve the learning ability of the neural network. In our numerical experiments, a Motion Capture System is utilized to assist the acquisition of training dataset. The experimental results demonstrate the efficacy of the proposed MSVAE-CNN based pose estimation method.

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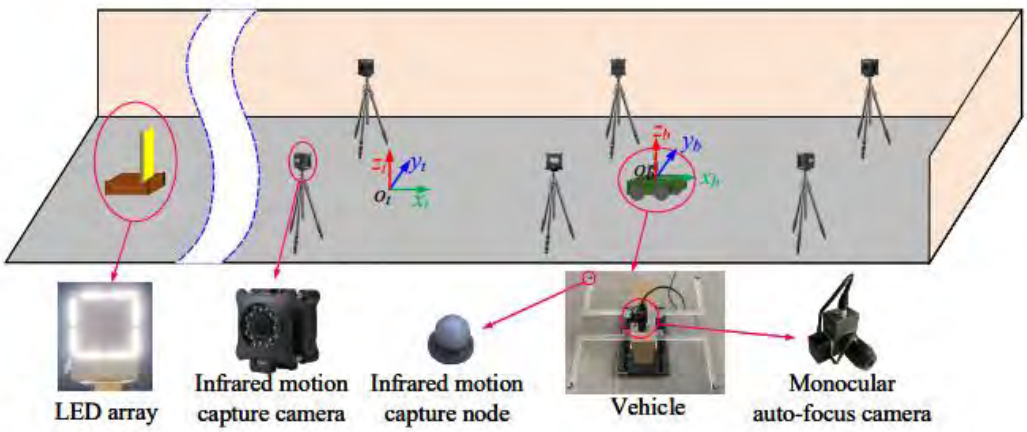

Fig. 5. Deployments of the dataset acquisition system in our experiments.

How NOKOV Contributes to the Research

In this work, the NOKOV Motion Capture System is utilized to obtain the 6-DoF pose of a vehicle (i.e., labels in the dataset), and a monocular monochrome auto-focus camera is attached to the vehicle and employed to capture the images of the artificial feature object (i.e., input images in the dataset). A visible-light LED array is used as the artificial feature object in our experiments to ensure the feasibility of the proposed pose estimation method in the underground tunnelling environment.

Citation Wu H, Liu S, Cheng C, et al. Multiscale variational autoencoder aided convolutional neural network for pose estimation of tunneling machine using a single monocular image[J]. IEEE Transactions on Industrial Informatics, 2021, 18(8): 5161-5170.

Link https://ieeexplore.ieee.org/abstract/document/9591347

Multisensor Multitarget Tracking and Collision Avoidance Based on the Labeled RFS Void Probability and KL-PaC Cost Function

Keywords

Collision avoidance, generalized labeled multi-Bernoulli (GLMB) filter, multisensor control, multitarget tracking, random finite set (RFS) void probability

Abstract

Existing sensor control methods for multisensor and multitarget tracking seldom consider comprehensive control strategy and collision avoidance between sensors and targets or between sensors together. In this article, we first propose a cost function for the multisensor control strategy, which includes Kullback–Leibler (K–L) divergence, detection probability, and sensor usage cost (KL-PaC cost function). Second, to solve collision avoidance between sensors and targets, we propose a collision avoidance strategy based on the labeled random finite set (RFS) void probability. The strategy is essentially to set up a safe region around the sensor or target and then combine the void probability and cost function in the safe region as the evaluation function. The final simulation and experimental results verify the effectiveness of the proposed approach.

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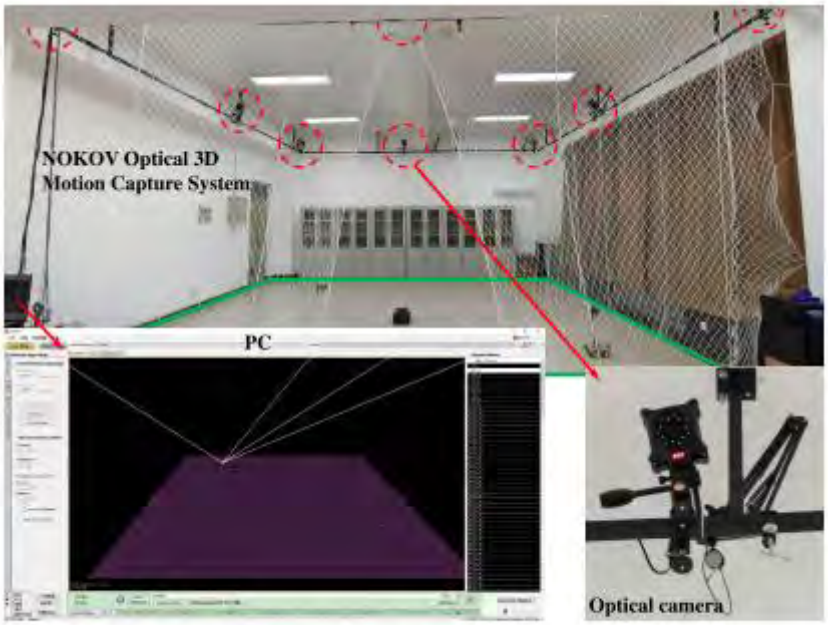

Fig. 16. NOKOV optical 3-D motion capture system.

How NOKOV Contributes to the Research

This section is the experimental part. We verify the feasi-bility of the proposed multitarget tracking multisensor controlalgorithm and the labeled RFS void probability collision avoid-ance strategy. In the experimental scene, the real positionsand velocities of the sensor and targets are provided by the NOKOV optical 3D motion capture system. The motioncapture system consists of eight optical cameras equidistantlydistributed over the square field, which can provide a positionaccuracy of 0.01 mm. The sampling time is set to 0.03 s. It is shown in Fig.16.

Citation Liu Q, Liu W, Zhao Z, et al. Multisensor Multitarget Tracking and Collision Avoidance Based on the Labeled RFS Void Probability and KL-PaC Cost Function[J]. IEEE Sensors Journal, 2023, 23(9): 9770-9785.

Link https://ieeexplore.ieee.org/abstract/document/10092456

Multi-target Association and Localization with Distributed Drone Following: A Factor Graph Approach

Abstract

Abstract—Vision-based multi-drone multi-object tracking technology enables autonomous target situational awareness for unmanned aerial systems. Distributed observer drones dynamically estimate the spatio-temporal states of multiple targets through collaborative sensor fusion, enabling simultaneous localization and persistent following of the target of interest in cluttered airspaces. The challenge lies in distinguishing targets in different drones' views and keeping the target of interest within the field of view. This paper proposes a factor graph method for joint multi-target association and localization with distributed drone following. Sensor measurements and control constraints are integrated into a probabilistic factor graph to solve the bundle adjustment and model predictive control, respectively. Both simulation and real-world experiments prove the effectiveness and robustness of our proposed approach.

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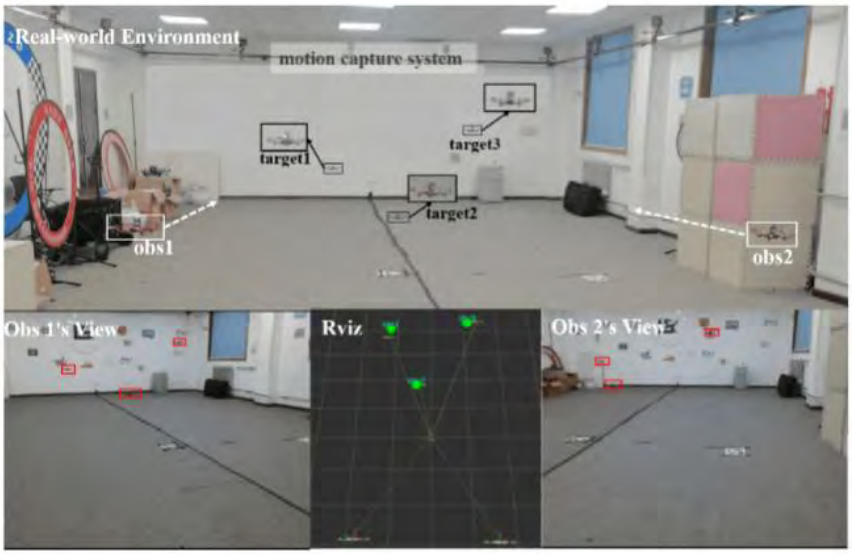

Fig. 5. Real-world settings.

How NOKOV Contributes to the Research

The real-world experiments are conducted usingDJI TT quadrotor drones andNOKOVMotion Capture System. The drones are employed as observers and targets, respectively. The motion capture system can obtain the precise motion states of the observer drones while providing high-precision ground truth positions of the targets. However, since a rough extrinsic calibration of the transformation matrix between the onboard camera coordinate and the drone body coordinate is performed using AprilTag \[15] and the motion capture system, the initial 6-DoF pose estimation of the drone's camera contains calibration errors. All the data and image streams are transmitted to and processed in the same computer as used in the simulation, based on ROS. A shot of the real-world experimental environment is illustrated in Fig. 5.

Citation K. Ye, W. Shao, Y. Zheng, B. Fang and T. Yang, "Multi-target Association and Localization with Distributed Drone Following: A Factor Graph Approach," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 18856-18863, doi: 10.1109/IROS60139.2025.11247561.

Link https://ieeexplore.ieee.org/document/11247561

Multi-target Coverage with Connectivity Maintenance using Knowledge-incorporated Policy Framework

Keywords

Training, Automation, Filtering, Conferences, Reinforcement learning, Maintenance engineering, Automobiles

Abstract

This paper considers a multi-target coverage problem where a robot team aims to efficiently cover multi-targets while maintaining connectivity in a distributed manner. A novel knowledge-incorporated policy framework is proposed to derive a distributed, efficient, and connectivity guaranteed coverage policy. In particular, a knowledge-guided policy network (KGPnet) is designed, which consists of observation attention representation, interaction attention representation, and knowledge-guided policy learning. Giving credit to the KGPnet, the connectivity guaranteed coverage policy can be applied to different number targets. Moreover, based on the knowledge of the algebraic connectivity and coverage rate, a comprehensive reward is designed to guide the training of the behavior of multi-target coverage with connectivity maintenance. Furthermore, since the policy learned through deep reinforcement learning (DRL) can not guarantee the connectivity of the robot team, a knowledge-nested policy filtering is designed to filter dis-connectivity policies to satisfy the connectivity constraint based on the knowledge model of connectivity maintenance. Various simulations are conducted to verify the effectiveness of the proposed method. Besides, numerous real-world experiments with three-wheel omnidirectional cars and a motion capture system are presented to demonstrate the practicability of the proposed method.

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How NOKOV Contributes to the Research

In order to verify the practicability of the proposed method in practical application, some real-world experiments are conducted. As shown in Fig.3 (b), a robot team consisting of three holomonic robots is used to test the derived policy. To improve the real-time of the policy generating, each robot is equipped with onboard computer (Nvidia Jetson TX2). In addition, the positions and velocities of the robots are provided by theNOKOVmotion capturesystem.

Citation Wu S, Pu Z, Liu Z, et al. Multi-target coverage with connectivity maintenance using knowledge-incorporated policy framework[C]//2021 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2021: 8772-8778.

Link https://ieeexplore.ieee.org/abstract/document/9562017

Multithreaded Asynchronous Deep Reinforcement Learning With Multisensor Fusion for Robot Collision Avoidance

Keywords

Deep reinforcement learning (DRL), multisensor fusion, premature collision prediction (PCP), robot collision avoidance

Abstract

To develop a safe and efficient navigation system of robotic vehicles in dynamic scenes, a new collision-avoidance method using deep reinforcement learning (DRL) is presented. First, a novel method of DRL based on multithreaded asynchronous proximal policy optimization (MAPPO) is developed. It can convert expensive online calculation into an offline training process, improving the sample efficiency during policy learning. Then, a multisensor fusion measurement (MSFM) method is presented by the combination of global reference path (GRP), laser scanner measurement (LSM), and motion energy (ME), to observe the state space of environment to maximum extent. By multireward refining at each timestep, the sparsity of rewards is avoided. On this basis, a collision-avoidance neural network (CANN) fused in multiscale and multilevel is devised to generate high-quality obstacle features, which can enable the MAPPO to master collision threat effectively. Besides, a premature collision prediction (PCP) module supervised by GRP is devised as an auxiliary task to learn high-level feature representation to further improve the safety during robot collision avoidance. Finally, a two-stage training strategy from 2-D Stage to 3-D Gazebo is presented to realize sufficient robot-environment interaction. This way, the policy model can maximize its degree of exploration in complex dynamic scenarios. Extensive navigation experiments are conducted on the complex simulation and real-world scenarios with a variety of obstacles, along with multiple comparative experiments to testify the effectiveness and robustness of our approach in robot collision avoidance. Experiment results reveal that our method can make farsighted navigation decisions in complex dynamic environments to dodge collisions successfully while moving toward the goal.

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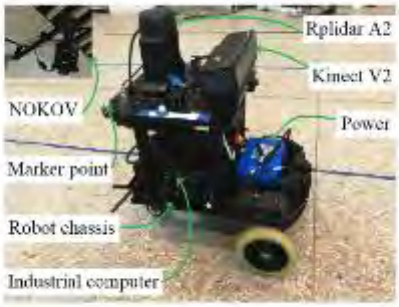

Fig. 16. Robot prototype for navigation experiments of collision avoidance.

How NOKOV Contributes to the Research

An onboard camera Kinect V2 is used for capturing RGB-D images, a Rplidar A2 is used as our 2-D laser scanner, and the NOKOV motion capture system is used for the indoor global localization.

Citation Sun C, Wu X, Su Y, et al. Multithreaded Asynchronous Deep Reinforcement Learning With Multisensor Fusion for Robot Collision Avoidance[J]. IEEE Transactions on Neural Networks and Learning Systems, 2025.

Link https://ieeexplore.ieee.org/document/10966458

Multi-UAV online path planning algorithm based on improved Hybrid A

Keywords

path planning, obstacle avoidance, anti-collision, velocity obstacle model, hybird A algorithm, potential field method

Abstract

Real-time path planning of multi-UAV includes obstacle avoidance and anti-collision, which is an important condition to ensure the coordinated operation of multi-UAV. This paper studies a multi-UAV online path planning algorithm based on improved Hybird A . Each UAV uses the Hybird A algorithm for distributed path planning. Through the collision risk assessment of the planned path, if there is a collision risk, the path adjustment is based on the defined UAV priority level and interactive information. In this paper, the existing two-dimensional velocity obstacle model is improved, and a three-dimensional velocity obstacle model suitable for 6-DOF UAV is constructed to calculate the safe speed range of UAV. As the optimization constraint condition, the path is adjusted based on the potential field method to achieve the effect of obstacle avoidance and collision avoidance. Finally, the simulation system and experimental platform are built to verify the real-time and stability of the proposed algorithm.

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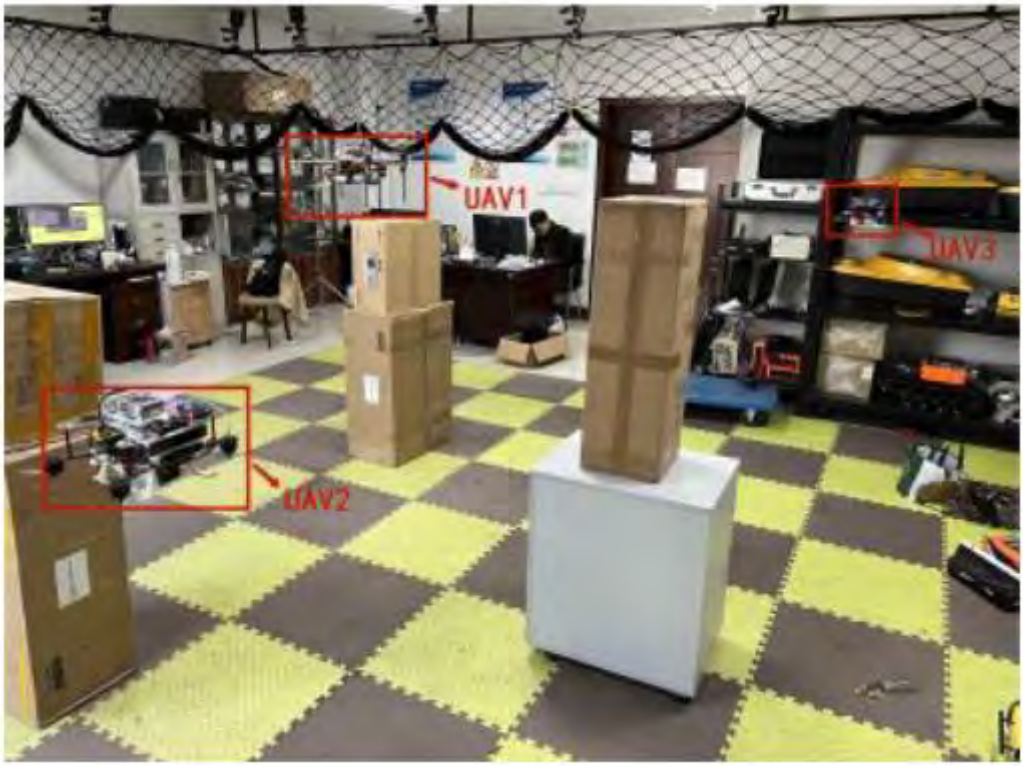

How NOKOV Contributes to the Research

The depth camera provides a depth map to sense the surrounding environment. NOKOV motion capture system provides accurate position estimation for each UAV. The on-board computer is responsible for the path information interaction between UAVs and running the path planning algorithm.

Citation Wang Z, Wan C, Lv X, et al. Multi-UAV online path planning algorithm based on improved Hybrid A[C]//2023 6th International Symposium on Autonomous Systems (ISAS). IEEE, 2023: 1-6.

Link https://ieeexplore.ieee.org/abstract/document/10164537

Multi-UAV-UGV Collision-Free Tracking Control via Control Barrier Function-Based Reinforcement Learning

Keywords

Abstract

This paper introduces a novel hierarchical control approach for feature matching, real-time tracking and inter-UAV collision avoidance in multiple unmanned aerial vehicle-unmanned ground vehicle (multi-UAV-UGV) collaborative tracking. Our approach divides into three layers: optimal feature matching, tracking control by reinforcement learning (RL), and collision avoidance using control barrier functions (CBFs). First, a distance cost matrix is cleverly constructed based on the feature matching capabilities of UAVs and UGVs to determine the optimal matching configuration. It allows UAVs to perform the tracking task while minimizing travel distance. Second, a RL-based tracker is developed to achieve precise real-time tracking without depending on UAV dynamic models. The tracker is trained in a single UAV-UGV environment, which reduces policy convergence difficulty by simplifying state space and interactions compared with training in complex multi-UAV-UGV scenarios. Third, a collision avoidance mechanism based on CBFs is introduced to transform RL commands into collision-free actions by solving a quadratic programming (QP) problem. Extensive simulations and real-world experiments demonstrate the effectiveness of the proposed approach.

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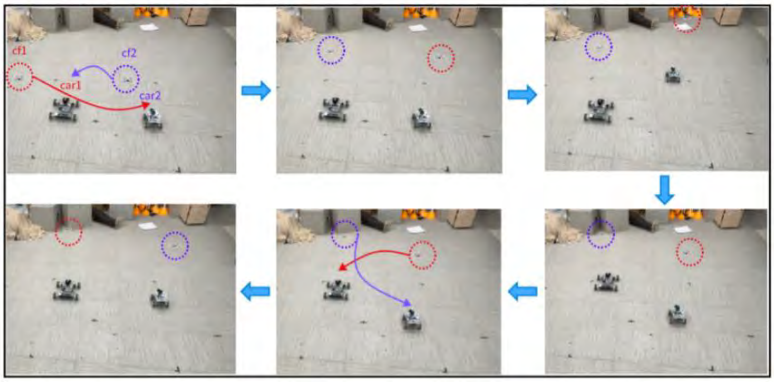

Fig. 6: The real-world tracking results of our approach using Crazyflie 2.1 and Mecanum-wheeled robots.

How NOKOV Contributes to the Research

We deploy this method on Crazyflie 2.1 and Mecanum-wheeled robots to achieve verification in real-world. The positions of Mecanum-wheeled robots as well as the positions and velocities of Crazyflie 2.1 are captured by the NOKOV Motion Capture System. This information is sent to a central processing computer, which executes the algorithm proposed in this paper to calculate the control instructions and then sends the commands to the Crazyfile 2.1 through high-frequency radio. The Mecanum-wheeled robots move randomly under human control. Initially, the features of the UAVs and the UGVs areFA= \[10,30]T and FG=\[70,28]T respectively. Therefore, as illustrated in Fig.6, UAVsA={1,2}track UGVsG={2,1}. Then, during the process, the features of the UGVs change toFG= \[20,50]T. At this moment, the UAVsA={1,2}reselect UGVs G={1,2}to track and maintain a safe distance.

Citation H. Xia, Q. Qi, X. Yang, X. Ju and H. Su, "Multi-UAV-UGV Collision-Free Tracking Control via Control Barrier Function-Based Reinforcement Learning," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 17115-17121, doi: 10.1109/IROS60139.2025.11247497.

Link https://ieeexplore.ieee.org/document/11247497

Nash Equilibrium Seeking for Multi-Agent Systems Under DoS Attacks and Disturbances

Keywords

Denial-of-service (DoS) attacks, disturbance rejection, multi-agent system (MAS), Nash equilibrium (NE) seeking

Abstract

In this article, the primary focus is on studying a Nash equilibrium (NE) seeking algorithm to maintain system resilience in multi-agent systems (MASs), which are subject to denial-of-service (DoS) attacks and disturbance. Furthermore, we demonstrate the performance of the algorithm in tolerating such attacks. DoS attacks are modeled using Markov processes, and their impact on interagent communication is investigated. The considered n-order MAS is unable to maintain normal communication links when subjected to DoS attacks. To address this issue, stability analysis is conducted to demonstrate the effectiveness of the proposed NE seeking algorithm in achieving secure control of MAS. Conditions for maintaining resilience under attacks are also provided. Finally, numerical simulations are performed on a satellite cluster system, and physical experiments are conducted using a wheeled robot ground platform to validate the effectiveness of the algorithm.

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Fig. 2. Wheeled mobile robots physical verification platform.

How NOKOV Contributes to the Research

In this section, we present two sets of experiments to validatethe proposed method on a physical platform. The physicalvalidation platform for wheeled mobile robots consists of anoptical 3-D motion capture positioning system (Nokov, Mars2H) equipped with 12 cameras with 2.2 megapixels, 380 Hzframe rate, 2048×1088 image resolution, and 2.4 ms latency. Amonitor computer (Lenovo savior blade 7000) and four-wheeledmobile robots (E-puck2) are also included in the platform. Fig.2depicts the physical validation platform.

Citation Zhong Y, Yuan Y, Yuan H. Nash equilibrium seeking for multi-agent systems under DoS attacks and disturbances[J]. IEEE Transactions on Industrial Informatics, 2023, 20(4): 5395-5405.

Link https://ieeexplore.ieee.org/abstract/document/10337768

Nonlinear Backstepping Trajectory Tracking Control for a Quadcopter with Experimental Validation

Keywords

nonlinear control, backstepping, trajectory tracking, unmanned aerial vehicle (UAV)

Abstract

This paper addresses the nonlinear control problem for a quadcopter. The proposed control strategy ensures effective trajectory tracking with ultimately bounded errors. A nonlinear controller employing a backstepping framework is designed to stabilize the quadcopter with damping effects. Simulation and experimental results demonstrate the controller's capability to maintain stability and accurately follow reference trajectory, validating the effectiveness of the proposed method.

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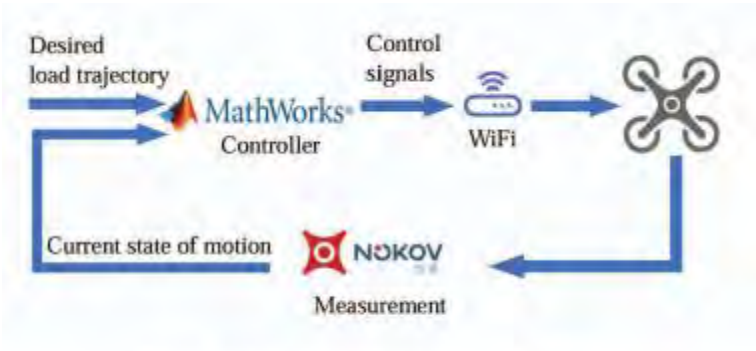

Fig. 8. Experimental control architecture

How NOKOV Contributes to the Research

The NOKOV motion capture system was used to acquire the motion states required for control. This motion capture system employs markers attached to the quad copter and operates with a dynamic capture mechanism that measures position and orientation at a frequency of 180 Hz, achieving sub-millimeter accuracy.

Citation Xiang S, Yang Z, Yu Y, et al. Nonlinear Backstepping Trajectory Tracking Control for a Quadcopter with Experimental Validation[C]//2024 China Automation Congress (CAC). IEEE, 2024: 4566-4571.

Link https://ieeexplore.ieee.org/document/10865011

OA-ECBVC: A Cooperative Collision-Free Encirclement and Capture Approach in Cluttered Environments

Keywords

Uncertainty, Robot kinematics, Heuristic algorithms, Robustness, Real-time systems, Safety, Collision avoidance

Abstract

This article investigates the practical scenarios of chasing an adversarial evader in an unbounded environment with cluttered obstacles. We propose a Voronoi-based decentralized algorithm for multiple pursuers to encircle and capture the evader by reacting to collisions. An efficient approach is presented for constructing an obstacle-aware evader-centered bounded Voronoi cell (OA-ECBVC), which strictly ensures collision avoidance in various obstacle scenarios when pursuing the evader. The evader can be efficiently enclosed in a convex hull given random initial configurations. Furthermore, to cooperatively capture the evader, each pursuer continually compresses the boundary of its OA-ECBVC to quickly reduce the movement space of the evader while maintaining encirclement. Our OA-ECBVC algorithm is validated in various simulated environments with different dynamic systems of robots. Real-time performance of resisting uncertainties shows the superior reliability of our method for deployment on multiple robot platforms.

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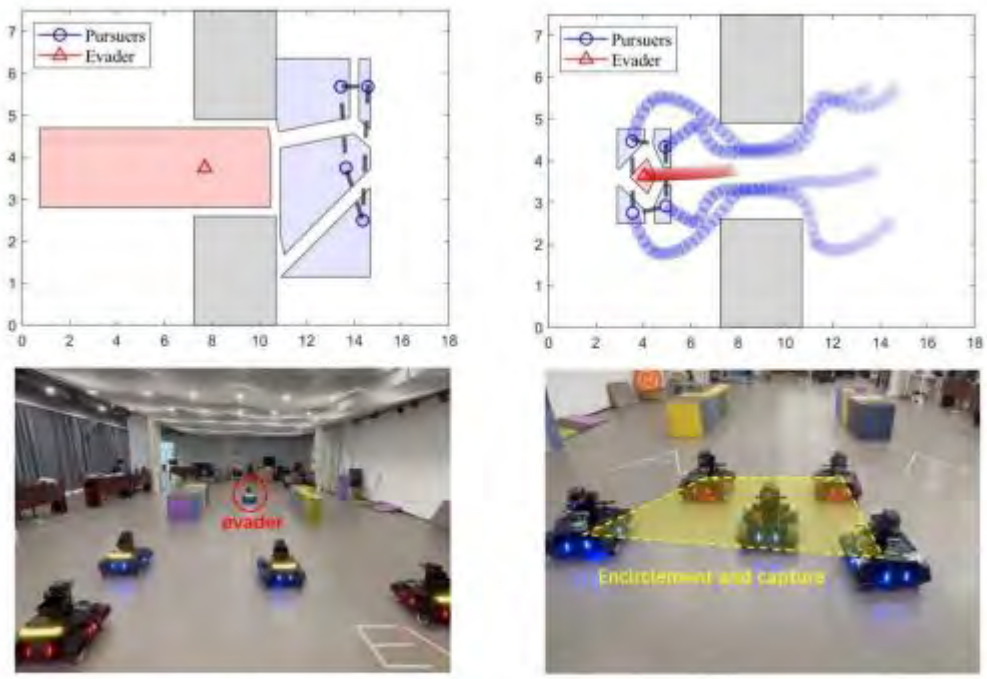

(a) t=0.0s (b) t_c=24.02s

Fig. 7: Four pursuers pursue an autonomous evader in a narrow space environment with the size of 8m×16m.

How NOKOV Contributes to the Research

In our decentralized multi-robot systems, each robot is equipped with an embedded computing platform (Intel i7CPU\@2.60 GHz) running ROS, allowing the robot to calculate its policy autonomously in real time. Information was transferred through the ROS network, and each pursuer only need to obtain the position of other robots via an external motion capture system (NOKOV) without knowing their policies.

Citation Wang X, Ding Y, Chen Y, et al. OA-ECBVC: A cooperative collision-free encirclement and capture approach in cluttered environments[C]//2023 62nd IEEE Conference on Decision and Control (CDC). IEEE, 2023: 5416-5422.

Link https://ieeexplore.ieee.org/abstract/document/10384055

Obstacle-Avoiding Path Planning and Tracking for Intelligent Vehicles Based on Kinematic Model

Keywords

intelligent vehicles, path planning, obstacle avoidance, trajectory tracking

Abstract

With the rapid development of intelligent driving technology, people have higher requirements for the safety of vehicle driving. The framework of this paper is divided into two layers. The upper layer is responsible for the path planning of the driving trajectory, and the lower layer is the trajectory tracking control. In the path planning layer, an obstacle model based on the potential energy function is proposed, while considering the sensing range of the vehicle, so that the vehicle can make an obstacle avoidance response in advance. The search efficiency is improved by combining PSO to segment the trajectory. The differential flatness of the intelligent vehicles is used to smooth the whole trajectory and segment boundaries, making the driving more comfortable. The trajectory tracking layer utilizes the kinematic model and ensures that the inputs are within the control boundaries. Simulation and real experiment based on the Quanser self-driving car (QCar) have been accomplished to prove the effectiveness of the proposed algorithm.

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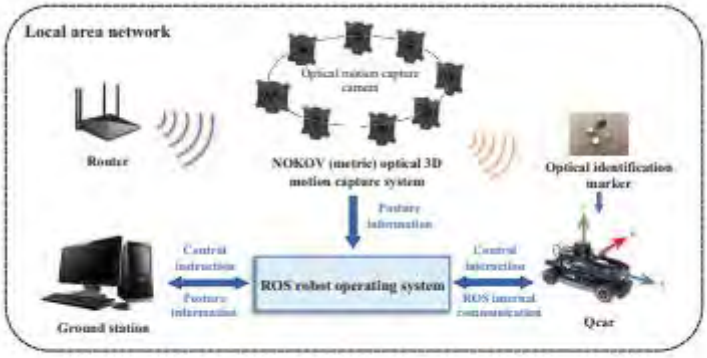

Fig. 6. Schematic diagram of QCar experiment process

How NOKOV Contributes to the Research

In this section, we evaluate the effectiveness of proposed control strategy in simulation as well as real experiment. MATLAB was used to calculate the control variables and simulate the motion effect of the four-wheel vehicle. For real experiment, we utilized the QCar to build the experimental platform.The positions of obstacles and QCar were given by NOKOV (metric) optical 3D motion capture system.The value of parameters used in the simulation and real experiment are shown in Table 1.

Citation Wang Z, Deng H, Zhang L. Obstacle-Avoiding Path Planning and Tracking for Intelligent Vehicles Based on Kinematic Model[C]//2023 IEEE 13th International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (CYBER). IEEE, 2023: 1218-1223.

Link https://ieeexplore.ieee.org/abstract/document/10256625

Obstacle-Aware Topological Planning over Polyhedral Representation for Quadrotors

Keywords

Smoothing methods, Shape, Data structures, Robustness, Real-time systems, Trajectory, Planning

Abstract

In this paper, we propose a novel mapping-planning framework for autonomous quadrotor navigation. First, a polyhedron-based mapping algorithm is presented to fully exploit the information of the onboard sensor data. Polyhedra are generated to approximate the segmented clusters of occupied voxels. Then, customized data structures are designed to extract information for motion planning in real time. With complete knowledge of the shape, position, and number of the observed obstacles, we can conveniently generate smooth trajectories with sufficient obstacle clearance along the most desired direction. Before searching for the initial path, a local topological graph is constructed to keep the path expanding in the most favorable topology class. The following path search is segmented based on the graph vertices, which allows fast convergence. The refined trajectory is obtained after smoothing, and large deviations are penalized in the formulated optimization problem to preserve the original clearance. Finally, we analyze and validate the proposed framework through extensive simulations and real-world quadrotor flights.

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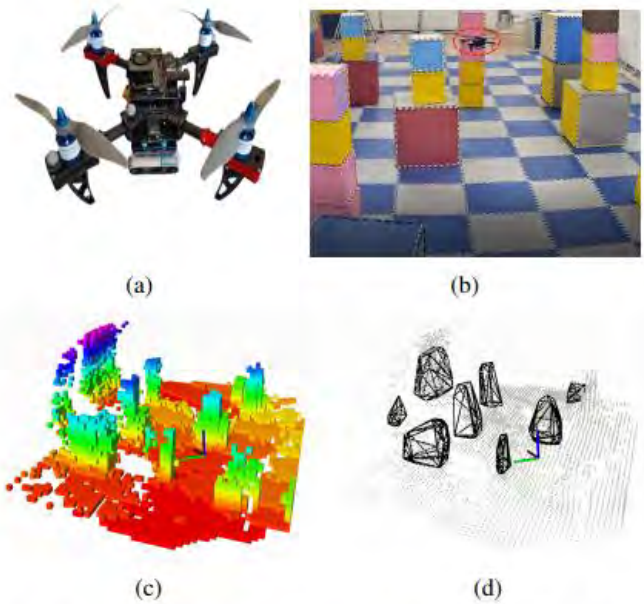

Fig. 8. (a) Hardware setting of our custom-built quadrotor. (b) A snapshot of the quadrotor crossing the unknown environment, and the average flight speed is $1.5m/s$ (c) The original occupancy grid map. (d) The polyhedral environment within the sensing range. The surface noise of the original map is covered by the generated planes, resulting in smoother trajectories.

How NOKOV Contributes to the Research

The custom-built quadrotor platform (shown in Fig. 8(a)) is equipped with a JETSON Xavier NX for onboard computing, a Pixhawk flight controller for stabilization, and a forward-facing RealSense D435i to provide depth images. The localization information is obtained from the NOKOV motion capture system. Real-world flight experiments are conducted in an unknown indoor environment as shown in Fig. 8(b). The original occupancy grid map and the corresponding polyhedron map are shown in Fig. 8(c) and Fig. 8(d), respectively. We abandon the occupied voxels below 0.15m and above 2.3m to segment the floor and the ceiling. The height constraint is posed during the path search. The collision check is implemented by regarding the quadrotor as a sphere with a radius of 0.2m.

Citation Gao J, He F, Zhang W, et al. Obstacle-aware topological planning over polyhedral representation for quadrotors[C]//2023 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2023: 10097-10103.

Link https://ieeexplore.ieee.org/abstract/document/10161295

On the Consistency of Multi-Robot Cooperative Localization: A Transformation-Based Approach

Keywords

Consistency, observability, cooperative localization (CL), error-state transformation

Abstract

This letter investigates the inconsistency problem caused by the mismatch of observability properties commonly found in multi-robot cooperative localization (CL) and simultaneous localization and mapping (SLAM). To address this issue, we propose a transformation-based approach that introduces a linear time-varying transformation to ensure the transformed system possesses a state-independent unobservable subspace. Consequently, its observability properties remain unaffected by the linearization points. We establish the relationship between the unobservable subspaces of the original and transformed systems, guiding the design of the time-varying transformation. We then present a novel estimator based on this method, referred to as the Transformed EKF (T-EKF), which utilizes the transformed system for state estimation, thereby ensuring correct observability and thus consistency. The proposed approach has been extensively validated through both Monte Carlo simulations and real-world experiments, demonstrating better performance in terms of both accuracy and consistency compared to state-of-the-art methods.

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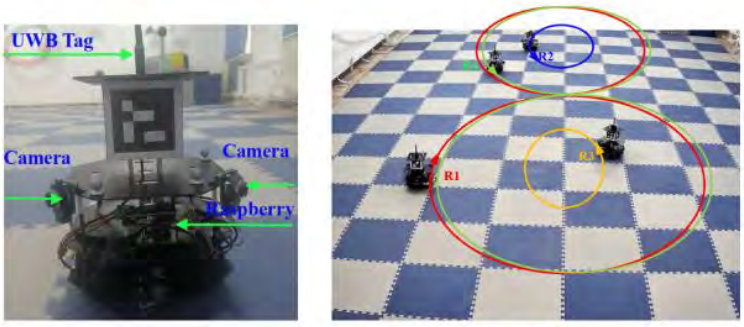

(a) (b)

Fig. 5. The robot team consists of four two-wheeled differential drive robots, each equipped with wheeled odometry, two wide-angle cameras, a UWB tag, and a Raspberry Pi 5 computer.

How NOKOV Contributes to the Research

To assess localization performance, weemploy the NOKOV motion capture system to track the position and orientation of these robots, which serve as ground-truth data.

Citation Hao N, He F, Tian C, et al. On the Consistency of Multi-Robot Cooperative Localization: A Transformation-Based Approach[J]. IEEE Robotics and Automation Letters, 2024.

Link https://ieeexplore.ieee.org/document/10759716

Onboard cooperative relative positioning system for Micro-UAV swarm based on UWB/Vision/INS fusion through distributed graph optimization

Keywords

micro-UAV swarm, Relative positioning, DGO

Abstract

In recent years, the swarm of micro Unmanned Aerial Vehicles (micro-UAVs) is becoming a research hotspot. As the basis of swarm autonomous flight, traditional relative positioning methods typically rely on external base stations or onboard sensors of high power consumption, the vast majority of which are not feasible on resource-constrained micro-UAVs flying in a complex environment. This article proposes a lightweight relative positioning system implemented on a micro-UAV platform weighing 150 g. We have developed a distributed graph optimization (DGO) scheme fusing the results of the onboard Ultra-Wideband (UWB) module, camera, and inertial sensors. A Delay Extended Kalman Filter (DEKF) is utilized to mitigate communication delays and enhance accuracy. This scheme enables micro-UAVs to collaboratively compute the relative position graph in real-time. Through real-world experiments, our system has achieved a relative positioning accuracy of 0.167 m, exhibiting significant potential for future swarm applications.

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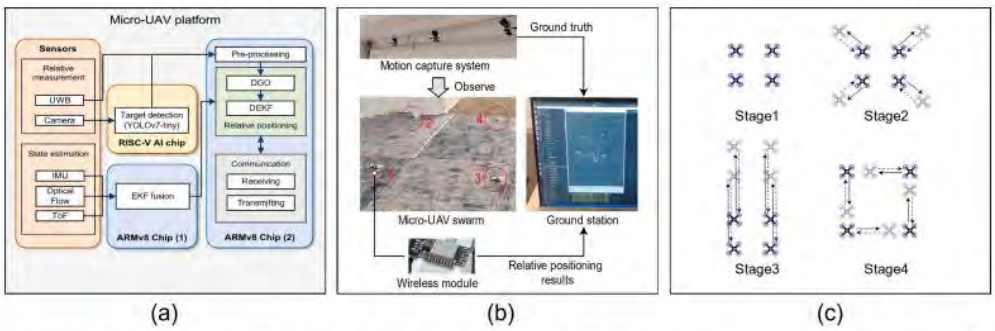

Fig. 11. Experimental scheme in the lab. (a) System architecture of micro-UAV platform. (b) The photographs of the experimental environment. (c) The pre-set trajectories of the micro-UAV swarm.

How NOKOV Contributes to the Research

The INS resultsand original sensor outputs were also recorded for comparison andanalysis. A NOKOV Mars2HW optical motion capture system acquiredthe ground truth and sent the true UAV positions to the ground station.The motion capture system was calibrated before the experiment, with ameasurement accuracy of + 0.25 mm, Note that the motion capturesystem did not participate in the onboard measurement and controlling processes of UAVs, to ensure the reliability of collected data.

Citation Xiong C, Lu W, Xiong H, et al. Onboard cooperative relative positioning system for Micro-UAV swarm based on UWB/Vision/INS fusion through distributed graph optimization[J]. Measurement, 2024, 234: 114897.

Link https://www.sciencedirect.com/science/article/abs/pii/S0263224124007826

On-demand Precise Tracking for Energy-constrained UAVs in Underground Coal Mines

Keywords

Unmanned aerial vehicle; unscented Kalman; filter; energy-efficient; on-demand precise tracking; coal mines.

Abstract

The precise tracking of unmanned aerial vehicle (UAV) in coal mines remains a challenging task that faces strict energy constraints. The existing approaches mainly focus on achieving better accuracy but ignore energy consumption. This paper proposes an on-demand precise tracking (OPT) framework based on the fusion of the ultra-wideband (UWB) and inertial measurement unit (IMU). The fusion unscented Kalman filter (fusion UKF) is devised for energy-efficient tracking with customized performance. First, OPT provides an adaptive adjustment mechanism of UWB signal transmission to trade-off between accuracy and energy consumption for UAV local positioning in coal mines. Second, we propose an on-demand trigger algorithm for UAV remote tracking to determine whether the data is transmitted to the ground server. Especially, the on-demand trigger condition is ameliorated owing to the existence of packet drops in complicated coal mines. Finally, extensive simulations in the Gazebo Platform and field experiments utilizing P440 UWB nodes in the indoor and coal mine laboratories have been conducted to verify the feasibility. Results show that OPT is efficient, practical and balances the performance and energy consumption under appropriate parameters. Compared with the existing event-triggered extended Kalman filter (ET-EKF) scheme, the accuracy is improved by 10.3%, and the communication rate is contracted by 11.4% in the coal mine environment.

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Fig. 11. The experiments in the indoor laboratory.

How NOKOV Contributes to the Research

Since the ground truth of position cannot be obtained directly in experiments, an optical motion capture system (NOKOV) that provides almost minor positioning errors is utilized to provide the reference position. We arrange eight cameras forming a square to capture the position of the UAV in the indoor laboratory.

Citation Zhang K, Chen P, Ma T, et al. On-demand precise tracking for energy-constrained UAVs in underground coal mines[J]. IEEE Transactions on Instrumentation and Measurement, 2022, 71: 1-14.

Link https://ieeexplore.ieee.org/abstract/document/9694638

Online Aerial Target Trajectory Prediction Using Multiple Model-Based Filter

Keywords

aerial target, kalman filter, quadrotor, trajectory prediction

Abstract

Because online aerial target trajectory prediction is crucial in quadrotor applications, this paper proposes a novel online trajectory prediction method. Specifically, two motion models are firstly formulated to estimate the motion state of the aerial target, then a multiple model-based filtering scheme is designed for the target to coalesce the prediction results from the two motion models. Compared with existing prediction methods, our method not only reduces the computation burden but also achieves more accurate and swifter prognostication of the target trajectory. The accuracy of the proposed prediction method is evaluated by both numerical simulations and real-world experiments, demonstrating the superior performance over the benchmark methods.

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Fig. 5. Real-world experiment.

How NOKOV Contributes to the Research

B. Real-world Experiment
Subsequently, we assess the practicality of our algorithmin real-world scenarios. To acquire the ground value of thetarget's odom, we use a quadrotor as the target and employa NOKOV motion capture system. As shown in Fig. 5,we manually manipulate the quadrotor to fly randomly in a10m×8m×3mindoor room. As seen in Fig. 6, our method can achieve higher accuracy in predicting the target's future trajectory.

Citation Lin H, Yang X, Xue E, et al. Online Aerial Target Trajectory Prediction Using Multiple Model-Based Filter[C]//2024 IEEE International Conference on Unmanned Systems (ICUS). IEEE, 2024: 32-36.

Link https://ieeexplore.ieee.org/abstract/document/10839977

Optimal Deployment of Multi-Robot Based Regional Positioning System Using Relative Bearing Measurement

Keywords

MR-RPS, distributed robot systems, optimal deployment, FIM, relative bearing measurement

Abstract

Recently, the Multi-Robot based Regional Positioning System (MR-RPS) utilizing cooperative localization have emerged as a promising paradigm in Global Navigation Satellite Systems (GNSS)-constraint region: robots first localize themselves using extravagant sensors and then serve as anchors to propagate their noisy positions via cooperative localization and communication with users using accessible devices. However, research on the optimal deployment strategies for bearing-only sensor-based MR-RPS, such as using cameras, remains limited. The bearing-only approach provides a cost-effective and energy-efficient alternative to range-based solutions such as radio systems. This letter proposes a distributed optimal strategy for MR-RPS equipped with bearing-only sensors to provide effective positioning services to the GNSS-limited scenarios. We first employ the Fisher Information Matrix (FIM) and D-optimality as the localization performance metric using the information received from the Multi-Robot System (MRS). Inspired by the coverage control problem from the Wireless Sensor Network, the optimal deployment of the MRS is then formulated into a locational optimization problem by integrating the value of D-optimality over the entire mission space. A distributed deployment strategy is thus developed, enabling each robot to iteratively compute optimal deployment strategies to enhance the overall performance for stochastically appearing users. Extensive simulations and physical experiments validate the resilience and effectiveness of the proposed method in delivering high-quality positioning services.

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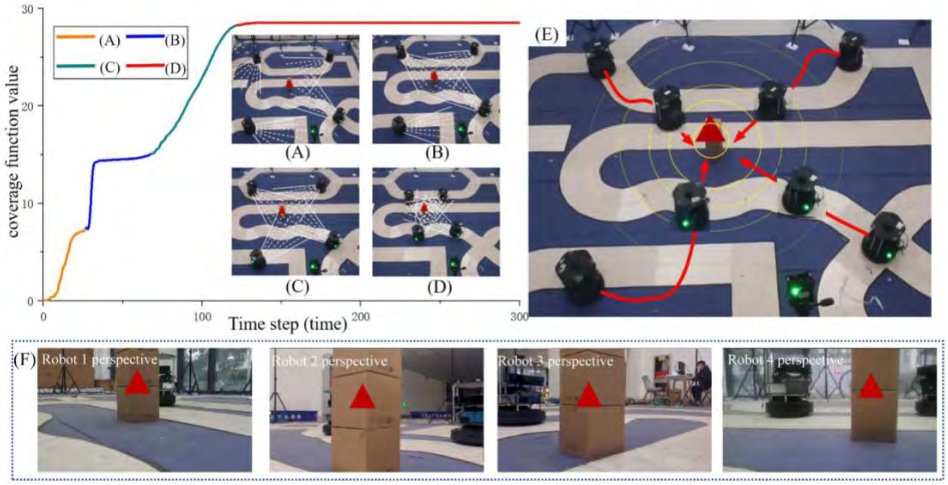

Fig. 4. Experimental results, (a)–(d) show the state of MRS at different moments, (e) is the moving trajectory of mobile robots, and (f) is the perspective of 4 mobile robots at the final moment.

How NOKOV Contributes to the Research

To further validate the feasibility of the proposed deployment strategy, we conducted a physical experiment.1The mission space is a 4 m×4 m 2D plane in the room. We set the central point of the density function at the midpoint of the mission space. As done in the first simulation, we employed four mobile robots to provide positioning services using mounted cameras. The purpose for all four robots is to autonomously form an optimal observation geometry to optimize the locational objective function in(2). To obtain precise pose information for all mobile robots within the mission space, we employed the NOKOV optical motion capture system. This system uses precisely placed cameras to track reflective markers on the robots and calculate their poses with high accuracy.

Citation Lin K, Zhang L, Wu K, et al. Optimal Deployment of Multi-Robot Based Regional Positioning System Using Relative Bearing Measurement[J]. IEEE Robotics and Automation Letters, 2025.

Link https://ieeexplore.ieee.org/abstract/document/11146604

Optimized control method for cooperative on-ramp merging of connected vehicles based on discretized spatial feature modeling

Keywords

On-Ramp merging, Discrete information, Expert system, Optimal control, Occupancy flow

Abstract

Vehicle-to-everything (V2X) technology can enable cooperative multivehicle control at traffic bottlenecks, such as ramp merging areas, to achieve increased safety and efficiency. However, the existing methods still face limitations in terms of optimizing efficiency, reducing complexity, and enhancing scalability in multilane scenarios. A discretized spatial feature modeling method for on-ramp merging areas is proposed in this study. By constructing occupancy flow features, uneven traffic features, and ramp flow radiation features, valuable information in space can be quantified. This information is then stored in discretized, equally sized rectangular segments and concatenated into a fixed-dimensional feature matrix. A multivehicle cooperative control method is developed on the basis of this model, incorporating a rolling optimization strategy with priority sequencing to evaluate and select the optimal actions for each vehicle. The control algorithm was comprehensively evaluated in mixed-traffic scenarios and demonstrated effectiveness. Compared with the benchmark algorithms, it achieved optimal and stable traffic efficiency, reducing the total completion time by at least 7.60% while ensuring safe vehicle spacing. Field tests further confirmed its feasibility.

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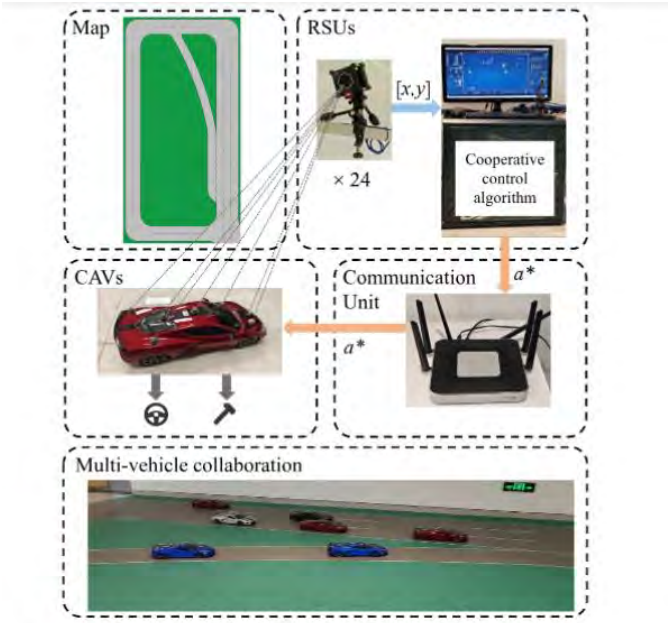

Fig. 9. Main interfacility relationships in the physical experimental platform.

How NOKOV Contributes to the Research

5.4. Field tests
Field tests are conducted by using a scaled-down physical experimental platform at a 10:1 ratio. The spatial relationships among the main components of the platform are depicted in Fig. 9. The upper-let corner displays the map (5.6 m x 10.8 m) used for the tests, and the upper-right corner shows the indoor simulated roadside units (RsUs), which consist of 24 NOKOV infrared motion capture cameras and a collaborative control server, "These motion capture cameras achieve precise vehicle localization by tracking the arrangement of fixed-shape reflective markers on the vehicles, The collaborative control server receives the status informatiorof all vehicles and runs the control algorithm proposed in this paper to generate the control outputs, These control outputs are then transmitted to the onboard computers of the intelligent vehicles via the communication unit, The onboard computers further integrate the control outputs with the underlving control protocols to calculate the steering angles and speeds, which are subsequently used toinstruct the chassis components to execute the corresponding actions

Citation Lei C, Tan X, Zhang J, et al. Optimized control method for cooperative on-ramp merging of connected vehicles based on discretized spatial feature modeling[J]. Transportation Research Part C: Emerging Technologies, 2026, 183: 105459.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001630116800002

Path Planning for Unmanned Aerial Vehicle Swarm Based on Electromagnetic Environment Sensing

Keywords

Unmanned aerial vehicle swarm, Electromagnetic environment sensing, Path planning, Deep reinforcement learning, Generative adversarial network (GAN), Weakly supervised learning

Abstract

Unmanned aerial vehicle (UAV) swarm is widely used in tasks such as post-disaster rescue and battlefield monitoring. These tasks are often executed in unknown or complex environments, necessitating the programming of safe and efficient paths for UAV swarm to ensure the completion of missions. To address the path planning problem for UAV swarm in unknown electromagnetic environment, we propose a multi-agent deep deterministic policy gradient algorithm based on environment sensing where a safe learning mechanism is designed by using control barrier function. Additionally, a weakly supervised learning-based generative adversarial network algorithm is employed to construct an electromagnetic environment sensing module. By using the algorithm we propose, UAV swarm can avoid zones with strong electromagnetic interference and guarantee inter-UAV collisions avoidance during task execution. Compared to reinforcement learning algorithm without environment sensing module and safe learning mechanism, the algorithm we propose reduces convergence time by approximately 2.5 times. Simultaneously, it prevents individual trial-and-error learning process from violating safety constraints, ensuring the safety of UAV swarm in unknown environment. Finally, we verified the effectiveness of our algorithm on the experimental platform which is constructed by using universal software radio peripherals and quadcopter UAVs.

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Figure 20 Experimental site.

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2\. Composition of experimental platform
The experimental platform consists of the following com-ponents: motion capture system, flight control station,and self-built quadcopter UAVs equipped with USRPs.The NOKOV motion capture system utilizes NOKOV ' sMares4H optical motion capture camera, as shown in up-per left corner of Figure 19; the quadcopter UAV is de-picted in upper right corner of Figure 19; and the USRPB210 is shown in lower part of Figure 19. Each UAV hasa unique rigid body for identification by motion capturesystem. The flight control station communicates withUAVs in a local network, enabling real-time control ofthe UAVs through data exchange.

Citation Li T, Ma Z, Shao J, et al. Path Planning for Unmanned Aerial Vehicle Swarm Based on Electromagnetic Environment Sensing[J]. Chinese Journal of Electronics, 2025, 34(4): 1156-1171.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001570255300007

PI-WAN: A Physics-Informed Wind-Adaptive Network for Quadrotor Dynamics Prediction in Unknown Environments

Abstract

Accurate dynamics modeling is essential for quadrotors to achieve precise trajectory tracking in various applications. Traditional physical knowledge-driven modeling methods face substantial limitations in unknown environments characterized by variable payloads, wind disturbances, and external perturbations. On the other hand, data-driven modeling methods suffer from poor generalization when handling out-of-distribution (OoD) data, restricting their effectiveness in unknown scenarios. To address these challenges, we introduce the Physics-Informed Wind-Adaptive Network (PI-WAN), which combines knowledge-driven and data-driven modeling methods by embedding physical constraints directly into the training process for robust quadrotor dynamics learning. Specifically, PI-WAN employs a Temporal Convolutional Network (TCN) architecture that efficiently captures temporal dependencies from historical flight data, while a physics-informed loss function applies physical principles to improve model generalization and robustness across previously unseen conditions. By incorporating real-time prediction results into a model predictive control (MPC) framework, we achieve improvements in closed-loop tracking performance. Comprehensive simulations and real-world flight experiments demonstrate that our approach outperforms baseline methods in terms of prediction accuracy, tracking precision, and robustness to unknown environments.

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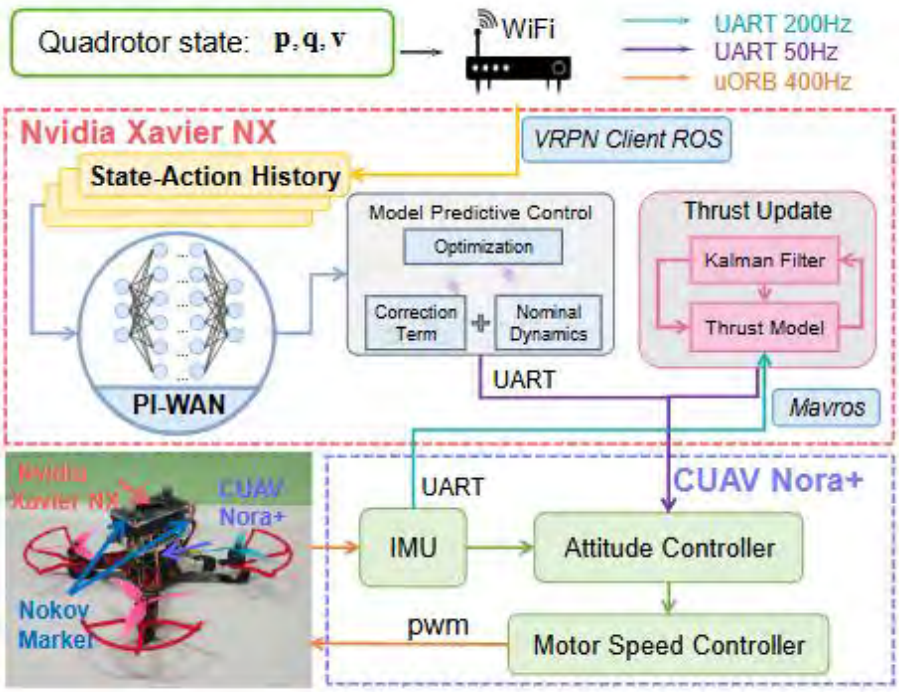

Fig. 7. The real-world experiment system. The quadrotor platform comprises the quadrotor frame, a CUAV Nora+ flight controller, and a Xavier NX onboard computer.

How NOKOV Contributes to the Research

We validate our controller augmented by PI-WAN usinga real-world quadrotor. The physical experimental platformis illustrated in Fig. 7. The quadrotor has a mass of 0.98kg,with a maximum thrust-to-weight ratio of 4.5. The stateof the quadrotor is provided by the Nokov motion capture system.

Citation M. Wang, B. Wang, Y. Niu and C. Wang, "PI-WAN: A Physics-Informed Wind-Adaptive Network for Quadrotor Dynamics Prediction in Unknown Environments," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 5413-5419, doi: 10.1109/IROS60139.2025.11247234.

Link https://ieeexplore.ieee.org/document/11247234

PPL-SLAM: RGBD-based point and parallel-line structural constrained for enhanced pose estimation

Keywords

RGB-D sensor, VSLAM, Camera pose estimation, Parallel line features, Feature-based localization

Abstract

The integration of point and line features has demonstrated strong potential in improving the accuracy and robustness of RGB-D SLAM systems. However, the geometric regularities formed by parallel line segments, which are prevalent in indoor man-made environments, are often ignored. This paper presents a novel RGB-D SLAM framework that incorporates geometric constraints from parallel line features at both local and global levels. At the local level, a geometry-aware reprojection model is proposed to capture distance consistency between parallel line pairs, improving the precision of pose estimation in challenging scenes. At the global level, directional information derived from clustered parallel lines is utilized to infer dominant scene axes, enabling reliable orientation tracking under varying structural conditions. The proposed system is evaluated on multiple public RGB-D benchmarks and a custom-built service robot platform. Experimental results indicate that the absolute trajectory error (ATE) is reduced by an average of 12% compared with state-of-the-art baselines. Ablation studies further verify that incorporating local and global parallel constraints yields an average reduction of 33.4% in trajectory error and 27.1% in drift. Moreover, the system operates in real time at 30 frames per second, demonstrating its suitability for practical robotic applications.

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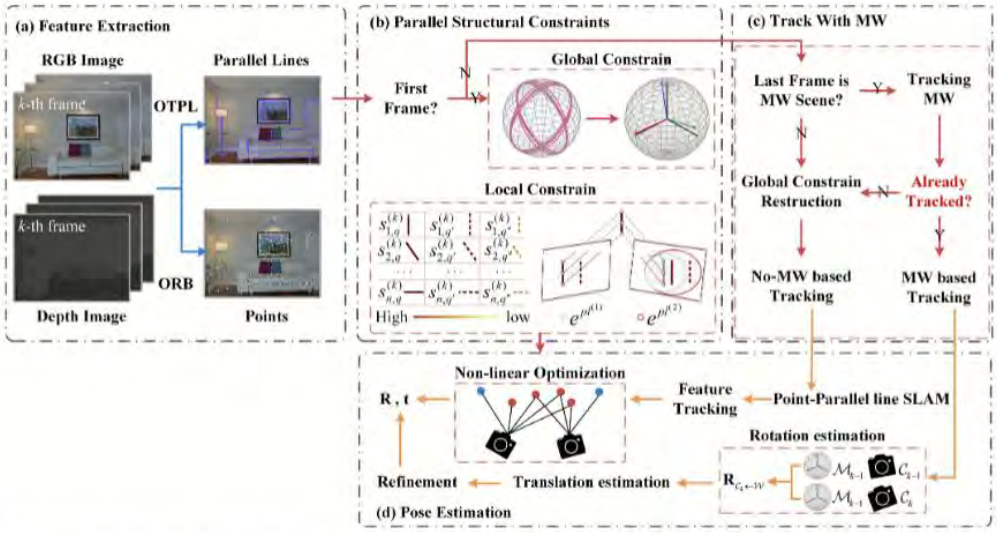

Fig. 1. Diagram of the PPL-SLAM framework. The system consists of (a) feature extraction, (b) parallel structural constraint construction, (c) track with MW, and (d) pose estimation modules. The tracking and pose estimation modules operate in parallel. Orange arrows denote pose optimization steps, red arrows indicate tracking operations, and blue arrows represent feature processing. Modules outlined with dashed lines indicate the core contributions of this work. Incorporate two concurrent threads, where the red box signifies the disparities between this discourse and the existing algorithm.

How NOKOV Contributes to the Research

4.4. Robustness evaluation in Real-World indoor scenarios
To assess the robustness of the proposed SLAM system in practical environments, we conducted experiments using a custom-built service robot platform. The platform features a modular chassis designed to flexibly integrate various sensors, a display, and onboard computing units for efficient data acquisition. Microsoft Azure Kinect DK was employed to capture synchronized RGB and depth images, while an ECHO mobile base served as the robotic platform. All algorithms were executed on a laptop embedded within the robot. We designed three representative structured indoor scenarios for evaluation: a home-like environment, an office workspace, and a long corridor. The home scenario was built in a controlled motion capture laboratory environment with typical furniture. Ground-truth trajectories were obtained using a high-precision NOKOV metric optical motion capture system with millimeter-level accuracy. High-reflectivity markers were affixed to the Azure Kinect DK, and eight infrared cameras mounted on the ceiling tracked its movement in real time. The experimental setup is shown in Fig. 12.

Citation Lee S J, Hwang S S. Elaborate monocular point and line slam with robust initialization[C]//Proceedings of the IEEE/CVF International Conference on Computer Vision. 2019: 1121-1129.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001632827700006

Predefined-Time Full-State Constrained Control for Mobile Robot Systems With Deferred Constraints

Keywords

Barrier Laypunov function, deferred constraints, full-state constraints, mobile robot systems (MRSs), predefined-time control

Abstract

This article studies the tracking control problem for a class of mobile robot systems (MRSs) with time-varying deferred constraints. First, a novel time-varying function is introduced to modify the original tracking error, which avoids the conservatism of the system initial values. Then, the modified errors are constrained within the preset deferred constraints by barrier Lyapunov function method. Furthermore, by using the fraction-power-based method, the novel predefined-time full-state constrained control scheme is designed. In the end, based on Lyapunov stability theory, it is demonstrated that the states will satisfy the preset constrains, all the signals in the closed-loop system are bounded in predefined-time, and the tracking errors can converge to the desired neighborhood of the origin in predefined-time. To validate the effectiveness of our designed control scheme, numerical simulations and practical platform experiments have been conducted. To ensure repeatability, our codes are open sourced on Github: https://github.com/JiannanChen/PTFSC-MRS.git.

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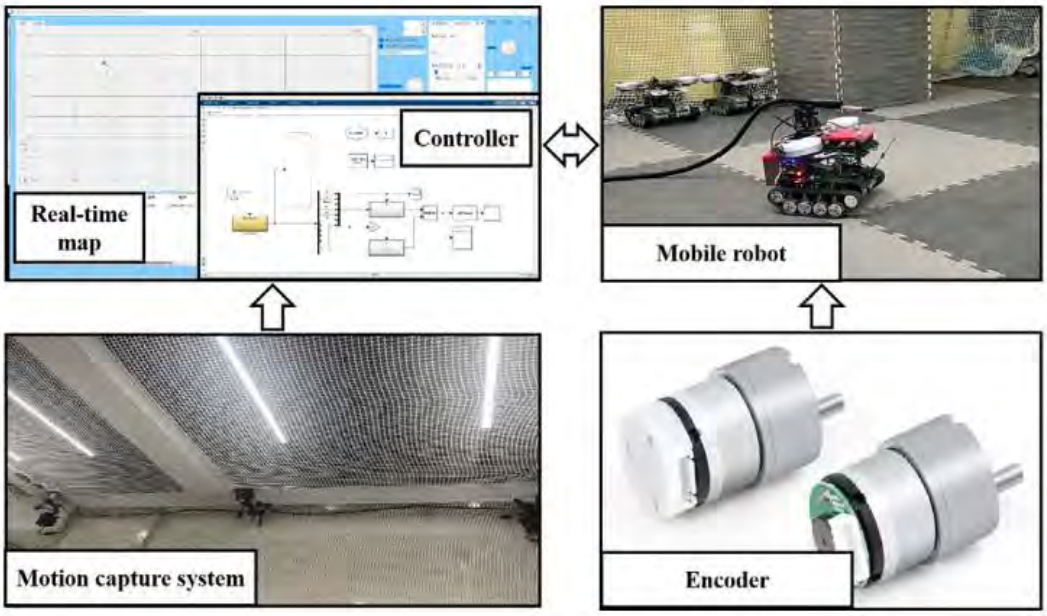

Fig. 4. System structure block diagram of our self-made mobile robot platform.

How NOKOV Contributes to the Research

Experiments are carried out on our self-made physical plat-form to further verify the effectiveness of our designed control scheme. Our platform comprises the Mobile Robot Unit, En-coder Unit, NOKOV Motion Capture System, and Controller Unit as illustrated in Fig.4. The Encoder unit and Motion Capture System respectively acquire velocity and azimuth in-formation of the mobile robot, which is periodically collected by the upper computer and transmitted to the Control unit. The control input signal is calculated in real-time based on Matlab.

Citation Chen J, Hua C, Mu D, et al. Predefined-time full-state constrained control for mobile robot systems with deferred constraints[J]. IEEE Transactions on Industrial Electronics, 2024.

Link https://ieeexplore.ieee.org/document/10631710

Preserving Relative Localization of FoV-Limited Drone Swarm via Active Mutual Observation

Abstract

Relative state estimation is crucial for vision-based swarms to estimate and compensate for the unavoidable drift of visual odometry. For autonomous drones equipped with the most compact sensor setting -- a stereo camera that provides a limited field of view (FoV), the demand for mutual observation for relative state estimation conflicts with the demand for environment observation. To balance the two demands for FoV limited swarms by acquiring mutual observations with a safety guarantee, this paper proposes an active localization correction system, which plans camera orientations via a yaw planner during the flight. The yaw planner manages the contradiction by calculating suitable timing and yaw angle commands based on the evaluation of localization uncertainty estimated by the Kalman Filter. Simulation validates the scalability of our algorithm. In real-world experiments, we reduce positioning drift by up to 65% and managed to maintain a given formation in both indoor and outdoor GPS-denied flight, from which the accuracy, efficiency, and robustness of the proposed system are verified.

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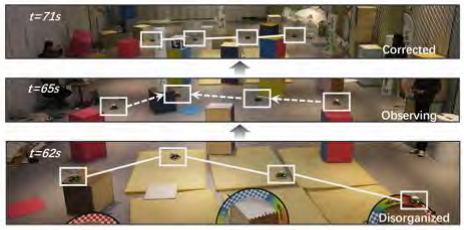

Fig. 9: Four drones conduct line formation flight in the indoor experiment.

How NOKOV Contributes to the Research

For the indoor experiment, the position information pro vided by the NOKOV motion capture system is introduced as the ground truth for evaluating the localization accuracy of our method.

Citation Guo L, Gongye Z, Xu Z, et al. Preserving relative localization of FoV-limited drone swarm via active mutual observation[C]//2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2024: 10423-10430.

Link https://ieeexplore.ieee.org/abstract/document/10801634

Privacy-Preserving Distributed Iterative Localization for Wireless Sensor Networks

Keywords

Distributed localization, privacy preservation, wireless sensor network (WSN)

Abstract

Effectively determining the accurate locations of sensor nodes while preserving data privacy is an interesting and challenging problem in the research of wireless sensor networks. On the basis of the well-performing distributed iterative localization framework in wireless sensor networks, this article proposes a dual privacy-preserving scheme based on node-intermittent updates and noises injection. A comprehensive analysis of the localization algorithm in terms of convergence and privacy-preserving performance is presented. It is theoretically demonstrated that the localization algorithm can achieve global accurate localization without leaking the privacy information of sensor nodes. At last, the performance of the privacy-preserving localization algorithm is verified by building an experimental platform containing six robots.

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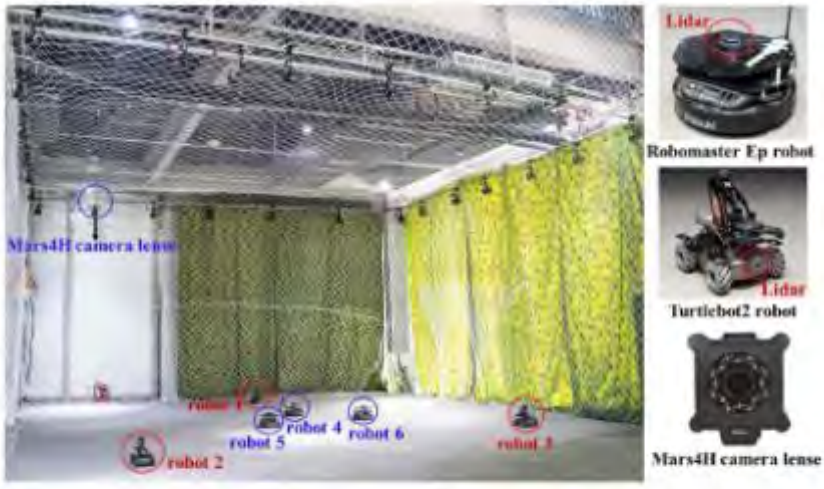

Fig. 3. Experimental platform composed of six robots and an NOKOV optical 3-D motion capture system, where robots 1,2,3 are the anchor nodes and robots 4,5,6 are the nonanchor nodes.

How NOKOV Contributes to the Research

The robots are randomly deployed over a 10 × 10 m2 square area, which is covered by a NOKOV optical 3-D motion capture system composed of 24 Mars4H camera lenses. Fig. 4 shows the robots' deployment and the motion capture system's coverage. The motion capture system can provide submillimeter level location data. In the 2-D space, each robot i's accurate location is decomposed into xi = (x1, x2). By the motion capture system, we can acquire all robots' accurate locations, i.e.

Citation L. Shi, W. X. Zheng, Q. Liu, Y. Liu and J. Shao, "Privacy-Preserving Distributed Iterative Localization for Wireless Sensor Networks," in IEEE Transactions on Industrial Electronics, vol. 70, no. 11, pp. 11628-11638, Nov. 2023, doi: 10.1109/TIE.2022.3231272.

Link https://ieeexplore.ieee.org/document/10002381

Proprioceptive-Based Multimode State Estimation for Wheeled-Quadruped Robot

Keywords

Multimode motion, proprioceptive state estimation, sensor fusion, wheeled–quadruped robot

Abstract

This article presents a novel multimode proprioceptive state estimation framework integrated with motor encoders and an inertial measurement unit (IMU) for wheeled-quadruped robot operating over long distances. The standard assumption of using nonslipping stance legs for state estimation in legged robots becomes invalid for wheeled-quadruped platforms due to their hybrid wheeled-legged morphology. To address this issue, a probabilistic slip model (PSM) that accounts for the additional displacement caused by wheeled motion is proposed. In addition, by constructing an offset wheeled-legged contact model, we estimate the contact position and velocity to reduce the accumulated errors resulting from inaccurate contact point estimation. Based on these foundations, we integrate wheel rotation measurements with the displacement induced by the wheeled configuration and employ a Kalman filter for state estimation. By incorporating reliable contact constraint (CC) into the observation model, our approach simultaneously compensates for vertical drift while maintaining estimation accuracy. To accurately assess wheel-ground contact status, a generalized momentum-based normalized method for contact detection is applied. The cumulative errors caused by premature or delayed landings of the stance legs are thereby minimized. Finally, our multimode state estimation methods show superior performance in indoor and outdoor scenarios, achieving at least a 1.75 times reduction in the root mean square error (RMSE) across all directions compared with existing methods.

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Fig. 10. Real motion trajectories from outdoor comparison experiments on satellite imagery. From left to right, the red trajectories represent wheeled motion, legged motion, and wheeled-legged coupled motion, respectively.

How NOKOV Contributes to the Research

The platform used in the experiments is the Lite3-W robot, which is developed based on the Lite3 quadruped robot from Deep Robotics. The Lite3-W features a total of 16 motors, with each leg having four degrees of freedom: abduction/adduction, thigh pitch, calf pitch, and wheel rotation. Each joint is equipped with both a motor encoder and a torque sensor. All experiments were conducted on an Intel NUC with an i7-1165G7 processor and 16GB of memory. The real position data from the indoor and outdoor experiments were obtained from NOKOV Motion Capture and the BeiDou MS-6222 RTK, respectively. The true ground contact information required for validating NCDM was sourced from the Bertec Force Plate 4060.

Citation Zhou S, Xiang B, Xie Z, et al. Proprioceptive-Based Multimode State Estimation for Wheeled-Quadruped Robot[J]. IEEE Sensors Journal, 2025.

Link https://ieeexplore.ieee.org/document/11031117

Race-car Circular Drifting with Onboard Sensor Positioning Using Static Anchors

Keywords

State estimation, Drifting control, onboard sensor, LiDAR localization

Abstract

In the field of autonomous driving, drifting control is of great importance for driving safety to deal with extreme situations. In order to better control the unmanned vehicle, it is necessary to have high-precision and high-frequency state information. To obtain state information, onboard sensors has the advantages of a lower cost, convenient deployment, indoor and outdoor versatility, etc. In this paper, we propose an onboard sensor estimation scheme using 2D LiDAR and IMU to support the control of a stable circular drifting task. We implement our method on a 1/10 scale radio control car. It can realize stable drift with a given center and radius, which illustrates the effectiveness of our method. A video of the cars performance can be found at https://www.bilibili.com/video/BV1Fg411z7XH/.

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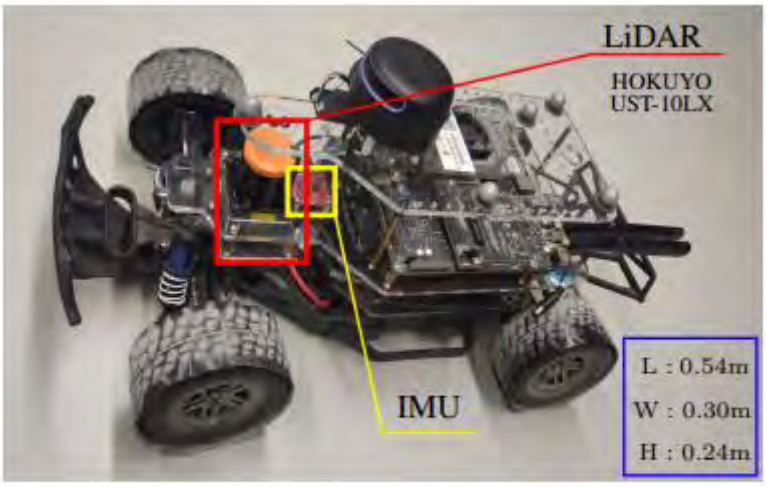

Fig. 7. The model racecar platform and sensor configuration.

How NOKOV Contributes to the Research

We completed a stable drift using only onboard sensors while using NOKOV's motion capture system to monitor the whole drift process and compare the data. Fig. 8 shows our exper-imental site, with the motion capture system lens mounted above and three cylindrical water buckets placed in the middleof the site, while the opaque white paper was pasted around the translucent buckets for LiDAR recognition.

Citation Qu J, Li Z, Ren X, et al. Race-car circular drifting with onboard sensor positioning using static anchors[C]//2023 3rd International Conference on Computer, Control and Robotics (ICCCR). IEEE, 2023: 378-384.

Link https://ieeexplore.ieee.org/abstract/document/10194167

Real-Time Multi-Modal Active Vision for Object Detection on UAVs Equipped With Limited Field of View LiDAR and Camera

Keywords

Aerial systems: applications, perception-action coupling, sensor fusion.

Abstract

This letter aims to solve the challenging problems in multi-modal active vision for object detection on unmanned aerial vehicles (UAVs) with a monocular camera and a limited Field of View (FoV) LiDAR. The point cloud acquired from the low-cost LiDAR is firstly converted into a 3-channel tensor via motion compensation, accumulation, projection, and up-sampling processes. The generated 3-channel point cloud tensor and RGB image are fused into a 6-channel tensor using an early fusion strategy for object detection based on a Gaussian YOLO network structure. To solve the low computational resource problem and improve the real-time performance, the velocity information of the UAV is further fused with the detection results based on an extended Kalman Filter (EKF). A perception-aware model predictive control (MPC) is designed to achieve active vision on our UAV. According to our performance evaluation, our pre-processing step improves other literature methods running time by a factor of 10 while maintaining acceptable detection performance. Furthermore, our fusion architecture reaches 94.6 mAP on the test set, outperforming the individual sensor networks by roughly 5%. We also described an implementation of the overall algorithm on a UAV platform and validated it in real-world experiments.

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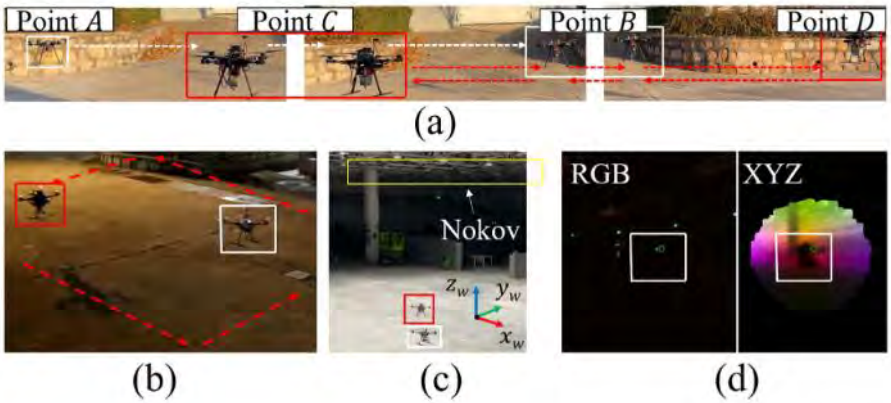

Fig. 5. Real-world experiments. Red box: the detector UAV and white box: the target UAV. (a) LF. (b) SF in LL conditions. (c) Indoor experimental environments. (d) The first-person view of the detector UAV of the circular flight in CD conditions.

How NOKOV Contributes to the Research

The NOKOV motion capture system was utilized to localize UAVs during indoor flight.

Citation C. Shi, G. Lai, Y. Yu, M. Bellone and V. Lippiello, "Real-Time Multi-Modal Active Vision for Object Detection on UAVs Equipped With Limited Field of View LiDAR and Camera," in IEEE Robotics and Automation Letters, vol. 8, no. 10, pp. 6571-6578, Oct. 2023, doi: 10.1109/LRA.2023.3309575.

Link https://ieeexplore.ieee.org/document/10233103

Reconfigurable Swarm System Design

Keywords

System construction · Functional verification · Platform development

Abstract

The mechanical, hardware, and software design of reconfigurable swarms is introduced in this chapter, and the design of their basic unit motion, docking, separation, and combination motion functions is described. Moreover, the positioning, communication, and coordination platform required for the experiments in Chaps. 3–8 is established.

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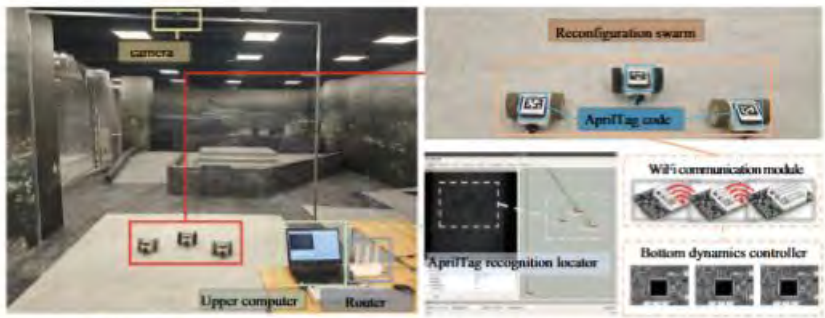
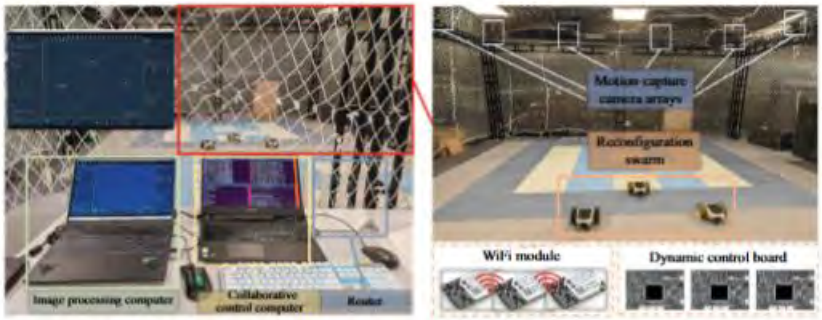


(a) High-precision global camera localization and communication scheme



(b) Motion capture platform localization and communication scheme

Fig. 2.3 RS unit modality localization and swarm communication scheme

How NOKOV Contributes to the Research

The second set is the NOKOV motion capture platform shown in Fig. 2.3b. During the experiment, the reflective ball Marker attached to the top of the modular unit is first recognized by the camera array, and then the NOKOV motion capture positioning algorithm is used to solve and obtain the pose of the modular unit. At this time, the control node of the host ROS system can subscribe to the modular unit pose published by the motion capture node of the image computer in the same local area network.

Citation Jiang, T., Zheng, Z., Yao, L., Ye, J., Wang, J., Feng, J. (2025). Reconfigurable Swarm System Design. In: Multi-modality Control of Reconfigurable Swarm. Springer, Singapore. https://doi.org/10.1007/978-981-95-0305-6_2

Link https://springer.publinks.top/chapter/10.1007/978-981-95-0305-6_2

RE-Formation: Resilient and Efficient Formation Planning in Large-Scale Distributed Aerial Swarms

Keywords

Large-scale formation, resilient swarms, efficient planning, sparse graphs, outlier rejection

Abstract

Due to the limited online computational resources and the inherent probability of hardware and software failures of real-world robots, large-scale formation planning faces two common challenges: computational intractability and agent failures. Based on the theory of sparse graphs and the maximum clique, we achieve a resilient and efficient formation planning (RE-Formation) to address these issues. To improve the computational efficiency of trajectory planning while ensuring flexible formation maneuvers, we introduce sparse graphs to describe connection relationships and present a sparse graph construction method with closed-form solutions. The sparse graphs ensure the G— lobal R— igidity for uniquely corresponding to a geometric shape and P–– reserve the main F–– eatures of complete graphs, denoted as the GRPF sparse graph. To prevent the impact of abnormal agents, the problem of eliminating abnormal agents is transformed into an outlier rejection problem that can be solved by computing the maximum clique. We approximate the maximum clique by periodically triggering the calculation of the maximum k - core to meet the real-time computational demands of large-scale swarms. We validate the performance through real-world experiments and implement formation planning with 100 drones in simulation. Benchmark comparisons and ablation experiments demonstrate the effectiveness of our method. Note to Practitioners — In this paper, we address the challenges of large-scale aerial swarm formation planning, focusing on computational efficiency and resilience to agent failures. Real-world swarm robots often face limitations in computational resources and are prone to hardware and software failures, which can severely impact formation coordination. Our proposed method uses sparse graphs that are globally rigid to reduce computational complexity while ensuring flexible formation maneuvers, and employs outliers rejection to eliminate abnormal agents, ensuring resilient collaboration.

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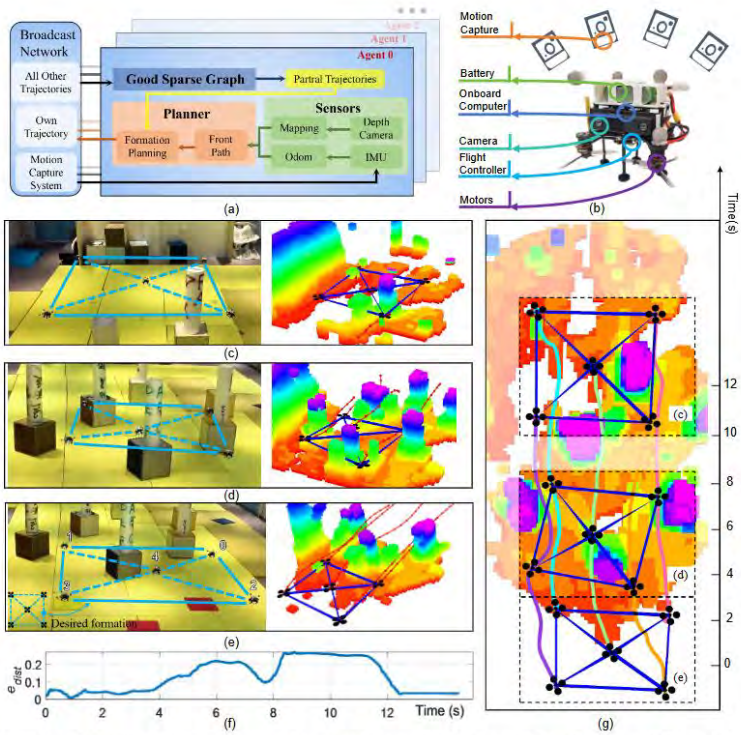

Fig. 14. (a) System architecture of distributed aerial swarm in real world experiments. (b) Quadrotor in real world experiments. (c) Screenshot and Rviz diagram of the final formation. (d) Screenshot and Rviz diagram of the formation corresponding to the 5 second. (e) Screenshot and Rviz diagram of the initial formation. (f) Formation error e_{dist} in the flight process. (g) Rviz diagram of a distributed swarm system of five drones in a square, which uses the sparse graph to model formation constraint, is traversing an unknown obstacle area.

How NOKOV Contributes to the Research

We integrate the sparse-graph-based trajectory planning method into the distributed physical aerial swarm system to maintain formation, and the architecture of the physical swarm system architecture is shown in Fig. 14(a). Each drone has independent modules for control, perception, and trajectory planning. The corresponding hardware includes the KAKUTE H7 Mini flight controller for control, the Intel RealSense D435 stereo camera for perception, and the NOKOV Motion Capture System for estimation. The mapping, estimation, and formation planning is run with an onboard computer Xavier NX in real-time.

Citation Zhou Y, Quan L, Xu C, et al. RE-Formation: Resilient and Efficient Formation Planning in Large-Scale Distributed Aerial Swarms[J]. IEEE Transactions on Automation Science and Engineering, 2025.

Link https://ieeexplore.ieee.org/abstract/document/11143553

Reinforcement Learning Compensated Filter for Multi-Agents Cooperative Localization

Keywords

cooperative localization, multi-agent reinforcement learning, value decomposition

Abstract

Accurate and real-time location tracking is vital for various applications in public safety and the military, particularly in search and rescue missions. Traditional filtering localization algorithms are more effective in linear environments and require precise initial estimates and system noise for optimal results. In complex and unreliable environments, these algorithms often yield poor localization results. To address these issues, this paper proposes a multi-agent collaborative localization algorithm based on reinforcement learning compensation filtering to tackle localization problems in complex environments and improve the robustness and accuracy of the localization algorithm. Specifically, this paper introduces a value decomposition-based reinforcement learning network for filtering compensation to reduce overall localization error and address the credit allocation problem in multi-agent reinforcement learning. This approach reduces the system's positioning errors and addresses credit allocation issues common in multi-agent reinforcement learning.

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Fig. 3: (a) The scene for physical experiment. (b) The auto-robot and sensors used for the test.

How NOKOV Contributes to the Research

To obtain a trained model, we performed 500 episodes of iterations during the model training stage in a simulation environment. Then, to verify the effectiveness of proposed MARL_CF, we set up four auto-robots [19] in a physical field (10m×10m), as shown in Fig. 3, and let them walk in two modes for 100 seconds, namely random walk and regular motion. The ground truth is captured by the NOKOV optics motion tracking system [20]. Furthermore, the trajectory paths and localization errors of the agents are drawn to evaluate the algorithm's performance.

Citation Wang R, Sun J, Xu C, et al. Reinforcement Learning Compensated Filter for Multi-Agents Cooperative Localization[C]//ICASSP 2024-2024 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP). IEEE, 2024: 101-105.

Link https://ieeexplore.ieee.org/abstract/document/10446775

Reinforcement Learning-Based Dynamic Coverage Control of Multi-Rotor UAVs With Safety Priority

Keywords

Safety critical systems, reinforcement learning, dynamic coverage control, multi-rotor UAVs

Abstract

This paper considers the dynamic coverage control of multi-rotor Unmanned Aerial Vehicles (UAVs) with the limited sensory range, which aims to collect sensor information from all points of interest in the given task area until the desired prescribed level is reached. However, the unknown environments are usually unavoidable for coverage task, where the presence of various obstacles and communication interferences affect the flight safety and communication stability of UAVs. Therefore, collision avoidance and connectivity maintenance are considered as the two safety issues in this paper, in which connectivity maintenance ensures the communication environment for UAVs to collaboratively accomplish task, and collision avoidance is used for UAVs to avoid obstacles and neighbors. In order to realize dynamic coverage control with safety constraints based on local environment information, this paper proposes the reinforcement learning-based algorithm with shield, where the shield designed by discrete-time Control Barrier Function (CBF) not only ensures the safety of the UAVs in the learning and control phases, but also maximizes the coverage performance of UAVs. In addition, each UAV only relies on local information to generate safe actions for advancing the coverage process during the execution phase. Finally, the effectiveness of the algorithm is verified by numerical simulations and physical experiment. Note to Practitioners—A typical application scenario of dynamic coverage control is search and rescue (SAR), in which UAVs equipped with multiple sensors focus on monitoring areas where trapped people may be present, e.g., anomalous areas detected by infrared sensors due to human body temperature. Since SAR always occurs in unknown environments, it is crucial to ensure the safety of UAVs during missions, of which the safety issues considered in this paper include collision avoidance and connectivity maintenance. To perform the SAR mission safely, we construct the CBF-based shield, which minimizes corrections the exploration actions of the UAVs and ensures the safety of the cluster during the mission. In addition, UAVs are difficult to obtain global environmental information in unknown environments and only rely on their sensors to collect local information. Therefore, the reinforcement learning algorithm with shield proposed in this paper adopts the centralized training and decentralized execution

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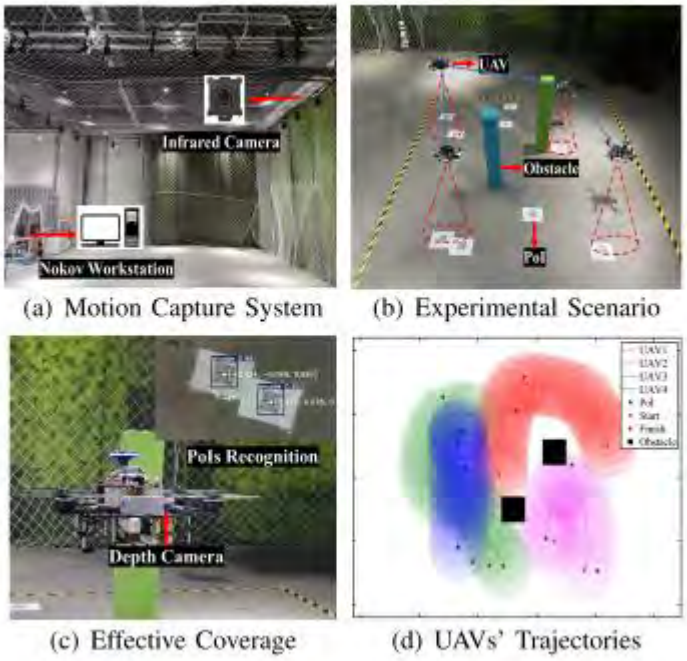
strategy, where the UAVs only need local observation information to plan their next actions. Physical experiments were also conducted to validate the feasibility of implementing the proposed algorithm using real UAVs.



(a) Motion Capture System (b) Experimental Scenario

(c) Effective Coverage (d) UAVs' Trajectories

Fig. 10. Physical experimentation with 4 multi-rotor UAVs and 10 PoIs.

How NOKOV Contributes to the Research

It is consisted of three key components: a NOKOV motion capture system, flight workstation, and custom multi-rotor UAVs. The NOKOV, which is shown by Fig. 10(a), serves as optical 3D motion capture system consisting of 44 infrared cameras and a workstation, and it can provide high-precision position data for the UAVs.

Citation Ma Z, You J, Zhang Y, et al. Reinforcement learning-based dynamic coverage control of multi-rotor uavs with safety priority[J]. IEEE Transactions on Automation Science and Engineering, 2024.

Link https://ieeexplore.ieee.org/document/10579936

Relative Measurement of Micro-UAVs Based on a Miniaturized 2D Profile Sensor System

Keywords

relative measurement, UAV, 2D profile sensor, fusion system

Abstract

Relative positioning serves as one of the key technologies for the autonomous flight of unmanned aerial vehicle (UAV) swarms. The mainstream vision-based methods in existing studies have high demands for computing power, energy, and size. When deployed on UAVs, especially micro-UAVs of several hundred grams, their accuracy and update rate are limited. In this study, we have developed a miniaturized high-precision relative measurement system utilizing a 2D profile sensor. The system achieves a relative angle measurement accuracy of around 1°. The results are fused with onboard ultra-wideband (UWB) system. Experiment results indicate the fusion system reaches a centimeter-level relative positioning accuracy, providing accurate relative coordinates for micro-UAV swarm cooperative missions.

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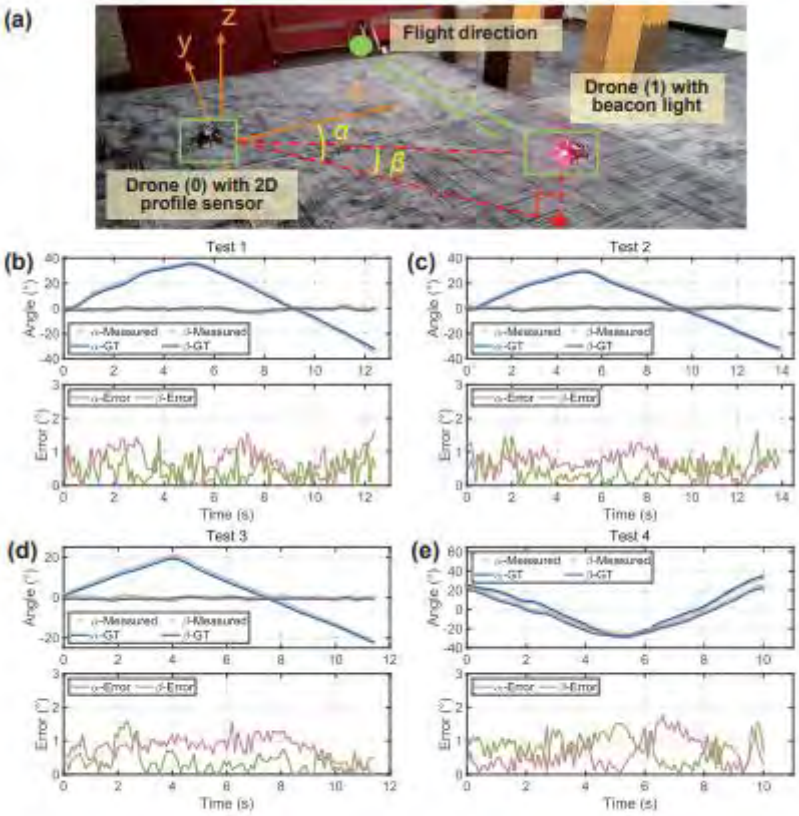

Fig. 3. Results of relative angle estimation. (a) The experimental setup. (b) -(e) The results and error curves of four tests.

How NOKOV Contributes to the Research

A NOKOV Mars 2HW optical motion capture systemwas utilized to acquire the ground truth (GT) of the positions of the drones. The sensor data and estimation results were sent to the ground station through wireless communication. A total of four tests were conducted.

Citation Xiong C, Lu W, Yao C, et al. Relative Measurement of Micro-UAVs Based on a Miniaturized 2D Profile Sensor System[C]//2024 IEEE SENSORS. IEEE, 2024: 1-4.

Link https://ieeexplore.ieee.org/abstract/document/10784626

Relative Positioning Method of Air-Ground Collaborative Robot

Keywords

Air-ground collaborative robot, Weighted Kalman Filter, Data fusion, Relative positioning

Abstract

This paper proposes a tethered UAV (Unmanned Aerial Vehicle) and UGV (Unmanned Ground Vehicle) relative positioning method based on the Weighted Kalman filter fusing tethered cable positioning data with AprilTag positioning data for the problem of accurate and robust positioning of UGV by UAV in the air-ground collaborative robotic system. The method firstly establishes the tethered cable positioning model and calibrates the external parameters and scale factor between the tethered cable positioning model and the AprilTag coordinate system for coordinate alignment. Then we establish the state-space equations of the air-ground cooperative robot system and build the measurement equations of the system based on the tethered cable positioning data and the AprilTag positioning data. Finally, tethered cable positioning data and AprilTag positioning data are filtered separately using a Kalman filter, and the output of the system is obtained by weighted sum of the filtered data. The experimental results show that the overall RMSE (Root Mean Square Error) of the relative positioning of UAV and UGV in this method is 0.064272 m, which is better than the output of tethered cable positioning model and Apriltag algorithm with the overall RMSE of 0.106797 and 0.098765 m, respectively. In addition, when the AprilTag marker is out of camera view, this method can still provide good relative position data between the tethered UAV and the UGV, which improves the positioning Robustness. This method is beneficial to the automatic take-off and landing of the tethered UAV, and its stable following UGV.

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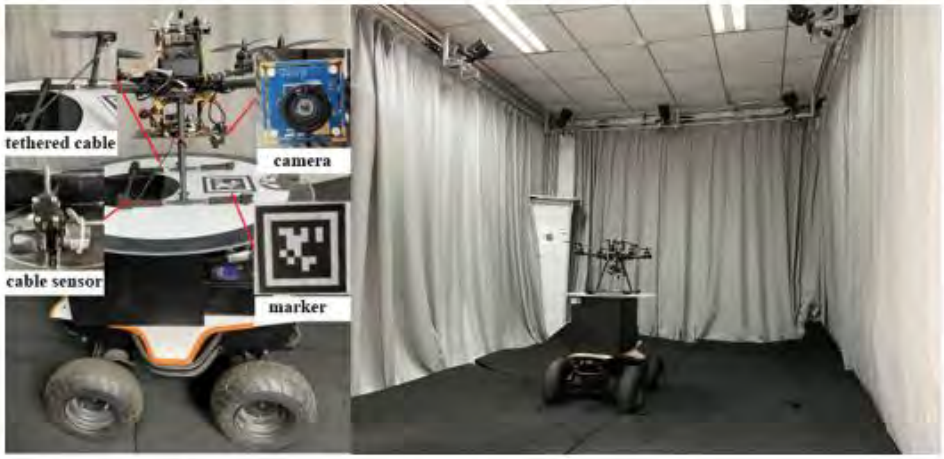

Fig. 3. Experimental platform and experimental site for air-ground cooperative robot system, where cable sensors can measure the length, azimuth and elevation angle of the tethered cable.

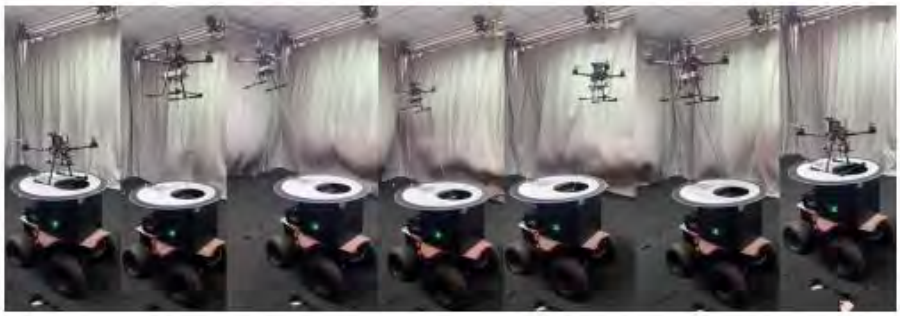

Fig. 4. Experimental procedure diagram while UGV does not move and the tethered UAV flies along rectangular trajectory.

How NOKOV Contributes to the Research

This experimental site contains a NOKOV optical 3D motion capture system com-posed of eight motion capture cameras, which is used to provide the ground truth of therelative position between UAV and UGV.

Citation Li X, Zhang H, Wang L, et al. Relative Positioning Method of Air-Ground Collaborative Robot[C]//International Conference on Guidance, Navigation and Control. Singapore: Springer Nature Singapore, 2022: 1200-1208.

Link https://link.springer.com/chapter/10.1007/978-981-19-6613-2_119

Research on Attack Detection Method for V2V System Based on Multi-dimensional TaylorSeries Expansion Framework

Keywords

Detection method, false data injection (FDI) attack, Taylor expansion, vehicle-to-vehicle (V2V) system

Abstract

Strongly stealthy cyberattacks in networked vehicle-to-vehicle (V2V) network environments often manifest themselves as small changes to data, which makes it difficult for existing methods to effectively detect such attacks. Although the initial impact of these attacks is minimal, they are capable of significantly disrupting the system over time. To address this issue, this article proposes a new data representation model for attack detection, aiming to overcome the limitations of existing detection methods. For subtle and persistent attack features, we present a multilevel data representation framework, which enables effective comparison of attack features at different scales by extracting features at various levels. Through hierarchical processing of features, these subtle changes are revealed at the microlevel, thereby enhancing the system's sensitivity to stealthy attacks. The experimental results show that the method in this article can effectively detect covert false data injection (FDI) attacks. Meanwhile, we compare the proposed method with the most recent competing methods, and the results demonstrate that our method has higher detection accuracy and stronger robustness compared with the existing methods.

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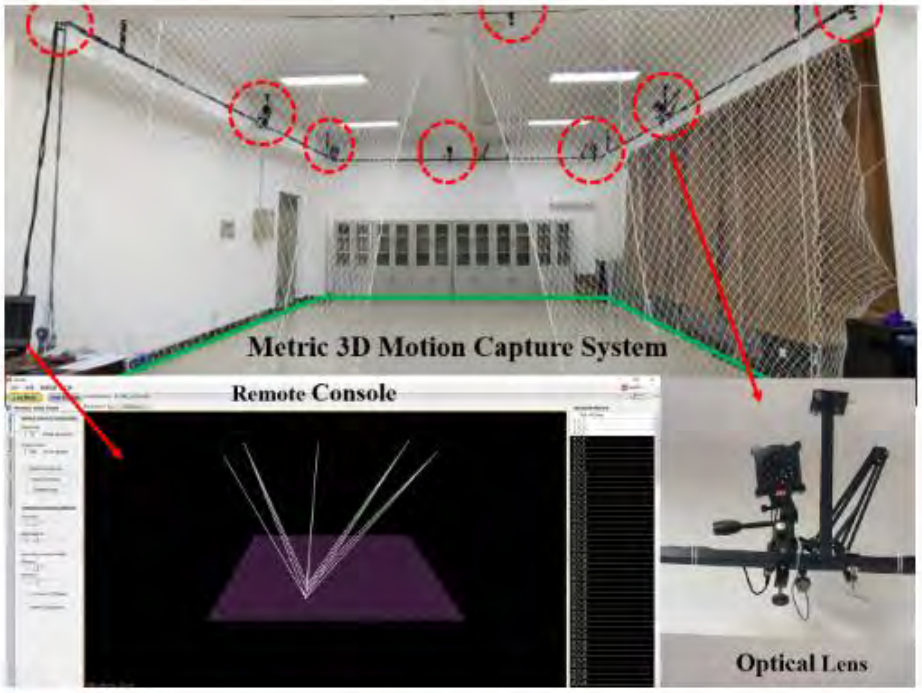

Fig. 14: Metric Optical 3D Motion Capture System.

How NOKOV Contributes to the Research

In this platform, an infrared high-precision motion capture system (Nokov) was used to obtain information on the vehicle's position, speed, and acceleration. Nokov updates data at a frequency of 60 Hz, with the motion capture system illustrated in the Fig 14,The actual vehicle fleet is shown in Fig 16.

Citation Wang D, Wen C, Liu W. Research on Attack Detection Method for V2V System Based on Multi-dimensional Taylor Series Expansion Framework[J]. IEEE Sensors Journal, 2025.

Link https://ieeexplore.ieee.org/document/10938211

Research on coding and decoding algorithm of binocular brain-controlled unmanned vehicle

Keywords

brain-computer interface, steady-state visual evoked potential, unmanned vehicle system, binocular stimulation

Abstract

Objective. With the rapid development of brain–computer interface (BCI) technology, steady-state visual evoked potential (SSVEP) has emerged as an effective method for high-efficiency information transmission. However, traditional single-frequency stimulation methods face limitations in command set scalability and visual comfort. Approach. To address these issues, we propose a novel binocular SSVEP stimulation paradigm for brain-controlled unmanned vehicles. (UV) This system uses a checkerboard and phase encoding for stimulus presentation, encoding a single target with two frequencies to expand the command set. The frequencies are set between 30–35 Hz to enhance visual comfort. By leveraging polarized light technology, each eye receives distinct frequencies, suppressing intermodulation components and reducing the stimulated area for each eye. We also introduce an improved filter bank dual-frequency task-discriminant component analysis (FBD-TDCA) algorithm. Main results. Experimental results show that, in a 15-command simulation, only six frequencies successfully encoded all commands, achieving comparable performance to traditional single-frequency paradigms. Furthermore, the FBD-TDCA algorithm outperformed existing methods such as filter bank task-related component analysis and filter bank canonical correlation analysis, achieving a classification accuracy of 89.27% ± 3.67 and an information translate rate of 163.87 ± 14.32 bits min−1−1, with statistical significance confirmed through paired t-tests. The system's practical application was further demonstrated in an online 12-command UV control task. Participants achieved an average classification accuracy of 90.34% ± 8.75%, with most maintaining low path deviation rates during navigation tasks. Significance. The proposed binocular SSVEP stimulation paradigm and FBD-TDCA algorithm address the limitations of traditional methods, offering enhanced command set scalability, improved visual comfort, and superior performance, paving the way for more efficient and user-friendly BCI applications in real-world scenarios.

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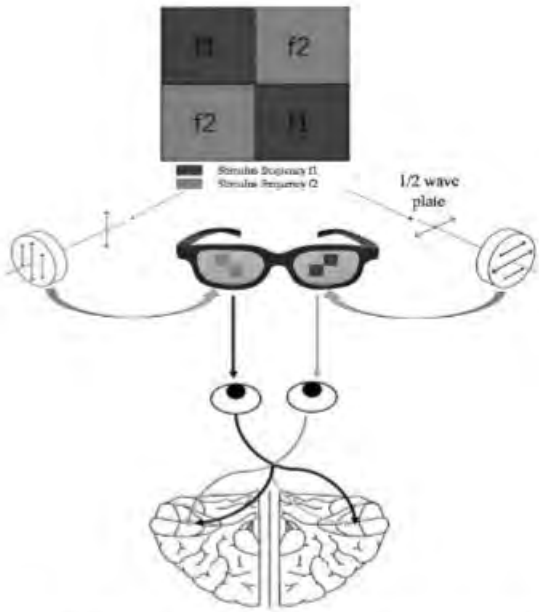

Figure 1. Schematic diagram of the working principle of the binocular vision paradigm system with a polarization display.

How NOKOV Contributes to the Research

5\. Data acquisition
This study used the Synamp2 EEG system for data acquisition. Since the experiment only differentiated between two types of visual stimuli without introducing spatial position information, it had minimal impact on the SSVEP response regions. EEG signals were recorded at a sampling rate of 1000 Hz from 21 occipital leads (P7, P5, P3, P1, Pz, P2, P4, P6, P8, PO7 PO5, PO3, POZ, PO4, PO6, PO8, O1, Oz, O2, CB1, CB2). All electrodes were positioned according to the international 10-20 EEG system, with the reference electrode located at CZ and the ground electrode on the forehead. Electrode impedance was maintained below 10 kΩ. The stimulus screen was an Alienware monitor (AW2518H, 27 inches, 2K resolution), modified with a 1/2 dial switch, and used in combination with circular polarized glasses. The UAV used in the experiment was the Robo Master EP, developed by DJI, an open-source product equipped with an official $DK. The online program was coded in Python, and the stimulus paradigm was developed and implemented in Vizard 7. The experiment's UAV tracking used the NOKOV (Measurement) optical 3D motion capture system (MARS).

Citation Xu F, Liu Y, Li Y, et al. Research on coding and decoding algorithm of binocular brain-controlled unmanned vehicle[J]. Journal of Neural Engineering, 2025.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001536512800001

RGB-D Vision Navigation via Motion Saliency Measurement and Twin Reprojection Optimization in Complex Dynamic Scenes

Keywords

Line feature, motion saliency measurement (MSE), robotic vehicle, twin reprojection (TR) optimization, vision navigation

Abstract

Localization in an unexplored environment is a fundamental capability for robotic vision navigation. However, due to the static world assumption, it still suffers the impoverishment of robustness and accuracy in complex dynamic workspaces. Moving objects, with indeterminate motion status in dynamic scenarios, usually increase the difficulty and complexity to the localization of the robotic vehicles. To address this problem, a robust and real-time RGB-D vision navigation system based on motion saliency measurement (MSM) and twin reprojection (TR) optimization is proposed to allow accurate localization for the robotic vehicles under complex dynamic scenes. Firstly, a novel saliency-induced dense motion removal (SDMR) method is developed to detect and eliminate the dynamic regions in RGB-D inputs, which can effectively filter out the outlier data that are associated with the moving objects. Then, a robust matching strategy for edge drawing lines (EDLines) feature is devised to acquire fine line inliers by constructing keypoint correspondence. Furthermore, the TR error is built by depth measurement for the line features. It is incorporated into a new error optimization function to achieve optimal pose estimation. The experimental results demonstrate that the SDMR can accurately detect dynamic objects and eliminate movement regions in complex dynamic scenarios. The proposed navigation system proves to attain at least 26% improvement of localization accuracy over other advanced dynamic navigation solutions. Test code is available on https://github.com/SunIMLab/TL-REE.

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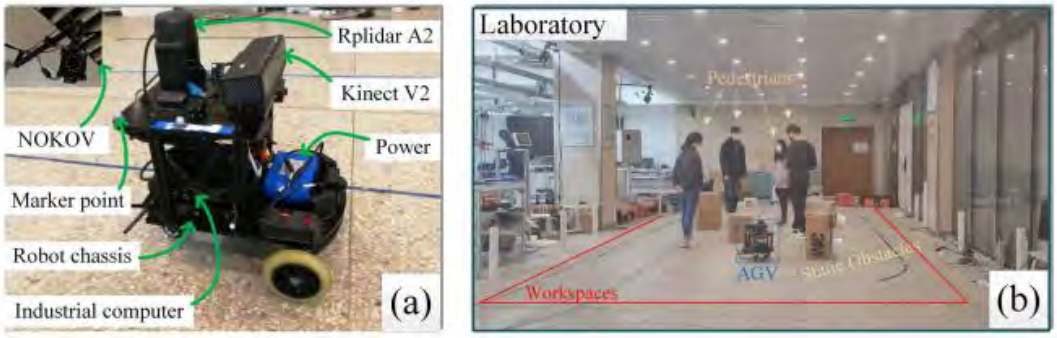

Fig. 15. RGB-D vision navigation in real-world dynamic scenes. (a) AGV prototype for navigation experiment. (b) Navigation process with static and dynamic obstacles.

How NOKOV Contributes to the Research

Meanwhile, the GT is provided by a high-accurac NOKOV motion-capture system. The image sequence is32-m long and contains 1100 frames. The estimation trajectories of OVD, RVWO, and our TL-REE, are shown in Fig. 16(a). We observe that the estimated trajectories of RVWO and OVD occur obvious drift, while that of ourTL-REE is similar to the GT. The consecutive absolute trans-lational errors of OVD, RVWO, and our TL-REE are plotted in Fig. 16(b).

Citation Sun C, Wu X, Sun C. RGB-D Vision Navigation via Motion Saliency Measurement and Twin Reprojection Optimization in Complex Dynamic Scenes[J]. IEEE Transactions on Instrumentation and Measurement, 2024.

Link https://ieeexplore.ieee.org/document/10731912

Risk-aware Trajectory Sampling for Quadrotor Obstacle Avoidance in Dynamic Environments

Keywords

Collision Avoidance; Motion and path planning; Aerial Systems; Perception and Autonomy

Abstract

Obstacle avoidance of quadrotors in dynamic environments, with both static and dynamic obstacles, is still a very open problem. Current works commonly leverage traditional static maps to represent static obstacles and the detection and tracking of moving objects (DATMO) method to model dynamic obstacles separately. The dynamic obstacles are pretrained in the detector and can only be modeled with certain shapes, such as cylinders or ellipsoids. This work utilizes our dual-structure particle-based (DSP) dynamic occupancy map to represent the arbitrary-shaped static obstacles and dynamic obstacles simultaneously and proposes an efficient risk-aware sampling-based local trajectory planner to realize safe flights in this map. The trajectory is planned by sampling motion primitives generated in the state space. Each motion primitive is divided into two phases: short-term planning with a strict risk limitation and relatively long-term planning designed to avoid high-risk regions. The risk is evaluated with the predicted future occupancy status, represented by particles, considering the time dimension. With an approach to split from and merge to global trajectories, the planner can also be used with an arbitrary preplanned global trajectory. Comparison experiments show that the obstacle avoidance system composed of the DSP map and our planner performs the best in dynamic environments. In real-world tests, our quadrotor reaches a speed of 6 m/s with the motion capture system and 2 m/s with everything computed on a low-price single board computer.

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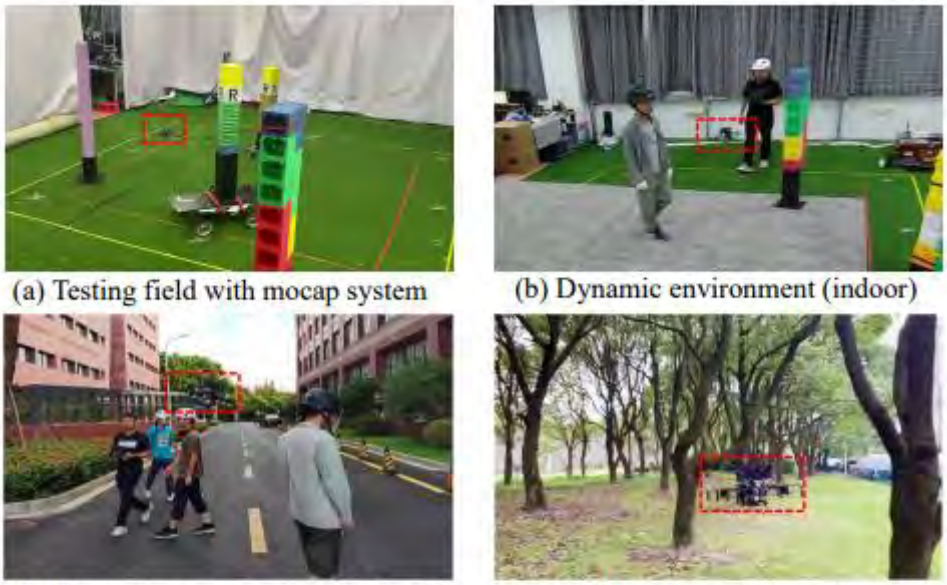

(a) Testing field with mocap system (b) Dynamic environment (indoor)

(c) Dynamic environment (outdoor) (d) Static environment

Fig. 9. Testing scenarios in the real world. In subplot (a), the position of the quadrotor and the position of obstacles are given by the motion capture system. The dynamic obstacles are two foam pillars mounted on mobile robots. Subplot (b) and (c) show two dynamic environments. Subplot (d) shows a static woods.

How NOKOV Contributes to the Research

Tests with the motion capture system: As is shown in Fig. 9 (a), two static obstacles and two dynamic obstacles were in the testing field. The dynamic obstacles moved with a constant velocity, about 1m/s for the faster one and 0.5m/s for the slower one. The Nokov motion capture system was used to capture the position of the quadrotor and the obstacles. The future occupancy status of the dynamic obstacles was predicted with the constant velocity model. The quadrotor was able to fly rapidly and safely in the tests. The maximum speed reached 6m/s. The corresponding velocity curve is shown in Fig. 10.

Citation Chen G, Peng P, Zhang P, et al. Risk-aware trajectory sampling for quadrotor obstacle avoidance in dynamic environments[J]. IEEE Transactions on Industrial Electronics, 2023, 70(12): 12606-12615.

Link https://ieeexplore.ieee.org/abstract/document/10034468

RMSC-VIO: Robust Multi-Stereoscopic Visual-Inertial Odometry for Local Visually Challenging Scenarios

Keywords

SLAM, vision-based navigation, sensor fusion

Abstract

We present a Multi-Stereoscopic Visual-Inertial Odometry (VIO) system capable of integrating an arbitrary number of stereo cameras, exhibiting excellent robustness in the face of visually challenging scenarios. During system initialization, we introduce multi-view keyframes for simultaneous processing of multiple image inputs and propose an adaptive feature selection method to alleviate the computational burden of multi-camera systems. This method iteratively updates the state information of visual features, filtering out high-quality image feature points and effectively reducing unnecessary redundancy consumption. In the backend phase, we propose an adaptive tightly coupled optimization method, assigning corresponding optimization weights based on the quality of different image feature points, effectively enhancing localization precision. We validate the effectiveness and robustness of our system through a series of datasets, encompassing various visually challenging scenarios and practical flight experiments. Our approach achieves up to a 90% reduction in Absolute Trajectory Error (ATE) compared to state-of-the-art multi-camera VIO methods.

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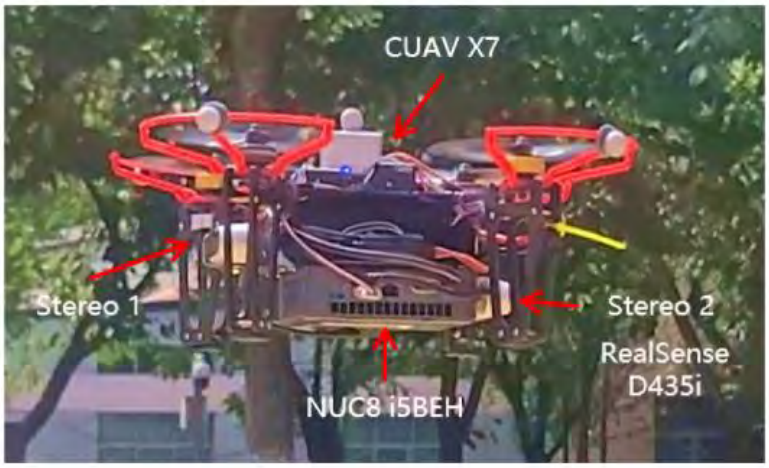

Fig. 4. Quadrotor drone employed in our experiment, equipped with two cameras featuring distinct orientations.

How NOKOV Contributes to the Research

For indoor sequences, we utilized NOKOV Motion Capture System to acquire ground truth poses with millimeter-level accuracy.

Citation T. Zhang, J. Xu, H. Shen, R. Yang and T. Yang, "RMSC-VIO: Robust Multi-Stereoscopic Visual-Inertial Odometry for Local Visually Challenging Scenarios," in IEEE Robotics and Automation Letters, vol. 9, no. 5, pp. 4130-4137, May 2024, doi: 10.1109/LRA.2024.3377008.

Link https://ieeexplore.ieee.org/document/10472018

Robo-centric ESDF: A Fast and Accurate Whole-body Collision Evaluation Tool for Any-shape Robotic Planning

Keywords

Shape, Trajectory planning, Real-time systems, Safety, Planning, Mobile robots, Reliability

Abstract

For letting mobile robots travel flexibly through complicated environments, increasing attention has been paid to the whole-body collision evaluation. Most existing works either opt for the conservative corridor-based methods that impose strict requirements on the corridor generation, or ESDF-based methods that suffer from high computational overhead. It is still a great challenge to achieve fast and accurate whole-body collision evaluation. In this paper, we propose a Robo-centric ESDF (RC-ESDF) that is pre-built in the robot body frame and is capable of seamlessly applied to any-shape mobile robots, even for those with non-convex shapes. RC-ESDF enjoys lazy collision evaluation, which retains only the minimum information sufficient for whole-body safety constraint and significantly speeds up trajectory optimization. Based on the analytical gradients provided by RC-ESDF, we optimize the position and rotation of robot jointly, with whole-body safety, smoothness, and dynamical feasibility taken into account. Extensive simulation and real-world experiments verified the reliability and generalizability of our method.

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How NOKOV Contributes to the Research

In real-world experiments, to validate our method can be applied to any-shape robots, we especially implement experiments with rectangle-shape (convex) and L-shape (non-convex) McNamee-based wheeled robots. Environment information is stored by a pre-build precise point cloud map and real-time localization is obtained by a NOKOV motion capture system.

Citation S. Geng, Q. Wang, L. Xie, C. Xu, Y. Cao and F. Gao, "Robo-Centric ESDF: A Fast and Accurate Whole-Body Collision Evaluation Tool for Any-Shape Robotic Planning," 2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Detroit, MI, USA, 2023, pp. 290-297, doi: 10.1109/IROS55552.2023.10342074.

Link https://ieeexplore.ieee.org/document/10342074

Robot Subgoal-guided Navigation in Dynamic Crowded Environments with Hierarchical Deep Reinforcement Learning

Keywords

Collision avoidance, graph attention networks, hierarchical deep reinforcement learning, robot navigation

Abstract

Although deep reinforcement learning has recently achieved some successes in robot navigation, there are still unsolved problems. Particularly, a robot guided by a distant ultimate goal is easy to get stuck in danger or encounter collisions in dynamic crowded environments due to the lack of long-term perspectives. In this paper, a novel subgoal-guided approach based on two-level hierarchical deep reinforcement learning with spatial-temporal graph attention networks (ST-GANets), called SG-HDRL, is proposed for a robot navigating in a dynamic crowded environment with autonomous obstacles, e.g., crowd. Specifically, the high-level policy, that models the spatial-temporal relation between the robot and the obstacles using the obstacles' trajectories by the designed high-level ST-GANet, generates intermediate subgoals from a longer-term perspective over higher temporal scales. The subgoals give a favorable and collision-free direction to avoid encountering danger or collisions while approaching the ultimate goal. The low-level policy, that similarly implements the designed low-level ST-GANet to implicitly predict the obstacles' motions, takes the subgoals as short-term guidance through an intrinsic reward incentive to generate primitive actions for the robot. Simulation results demonstrate that SG-HDRL using ST-GANets has better performances compared with state-of-the-art baselines. Furthermore, the proposed SG-HDRL is deployed to an experimental platform based on omnidirectional cars, and experiment results validate the effectiveness and practicability of the proposed SG-HDRL.

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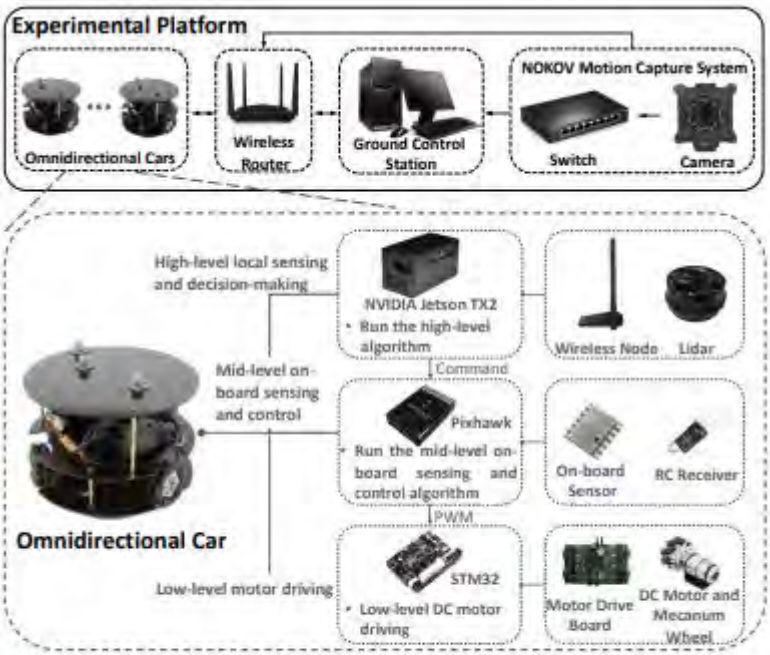

Fig. 8. Experimental platform based on omnidirectional cars.

How NOKOV Contributes to the Research

The experimental platform consists of omnidirectional cars, a ground control station, a wireless router and a NOKOV motion capture system.
The NOKOV motion capture system is used as the indoor positioning system which can provide milimeter-level position measurement.
For example, the ground control station sends commands to each car through the router, and the NOKOV motion capture system sends the position and velocity of the cars to each car through the router.
The states of the cars are obtained through NOKOV Motion Capture, and distributed to all the cars.

Citation Zhang T, Liu Z, Pu Z, et al. Robot subgoal-guided navigation in dynamic crowded environments with hierarchical deep reinforcement learning[J]. International Journal of Control, Automation and Systems, 2023, 21(7): 2350-2362.

Link https://link.springer.com/article/10.1007/s12555-022-0171-z

Robust safe control for nonlinear quadrotor with a cable-suspended payload systems via control barrier function and disturbance estimator

Keywords

Quadrotor with a cable-suspended payload system, Safe control, Control barrier function, Disturbance rejection

Abstract

In quadrotor with a cable-suspended payload transportation tasks, achieving real-time safe control of the system is significantly challenging due to the system's strong nonlinearity and underactuated nature. This challenge is further amplified by the presence of model uncertainties and external disturbances. To address this issue, we first derive the safe condition of the quadrotor with a cable-suspended payload system subjected to obstacles and construct a control barrier function accordingly. Then, considering the impact of disturbances on control performance and system safety, a unified control barrier function-uncertainty and disturbance estimator framework is developed to simultaneously ensure safety and robustness. Finally, the safe control problem is reformulated as a modified quadratic program to guarantee its engineering feasibility and is solved online using the IPOPT solver. The proposed methodology is deployed on a custom-built quadrotor, and extensive experiments in the environment with obstacles and disturbances are implemented to validate its effectiveness.

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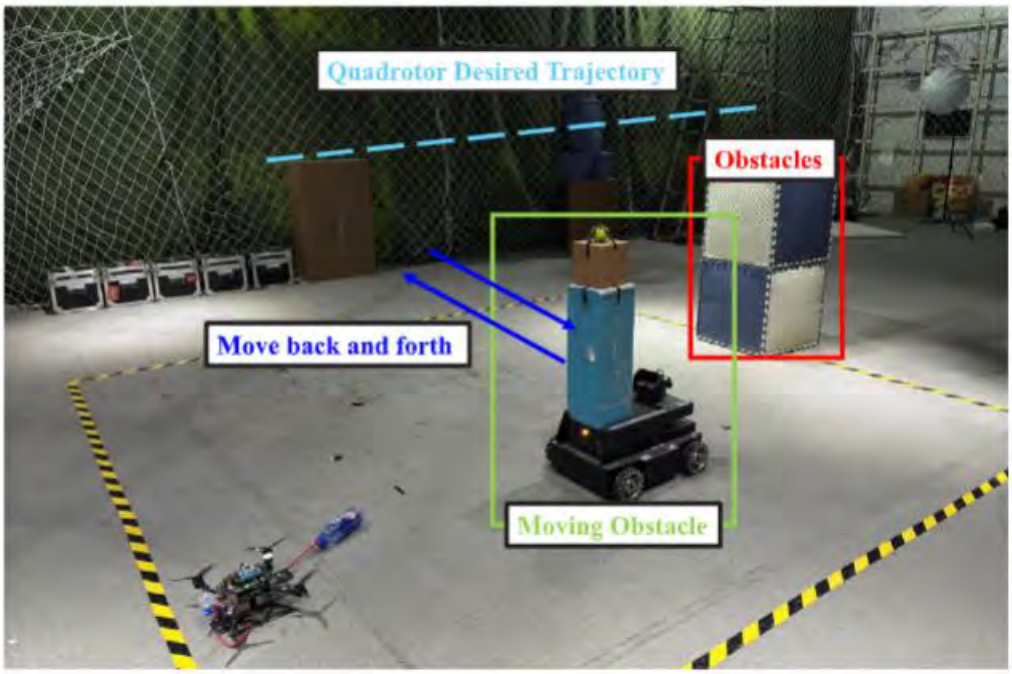

Fig. 10. Experiment setup for Case 3.

How NOKOV Contributes to the Research

During experiments, the quadrotor's low-level controller, including an attitude controller and a mixer, is handled by the PX4 autopilot firmware (Dronecode, 2024) (version vl.14), which executes acceleration commands generated by the proposed safe controller. To obtain the accurate quadrotor states, the experiments are conducted in an indoor environment equipped with a NOKOV Motion Capture (MoCap) System. Forty-four MoCap cameras track the reflective markers on both the quadrotor and the payload, calculating their position and linear velocity information in the local frame. The MoCap system operates at a frequency of 150 Hz and provides sub-millimeter positioning accuracy. Through the Virtual Reality Peripheral Network (VRPN) protocol, the captured quadrotor states are streamed to the onboard computer as odometry data. It is worth mentioning that in the experiments, the payload swing angles and angular velocities are derived through geometric calculations using the relative positional and kinematic data between the quadrotor and payload.

Citation Zheng Z, Tong S, Zhang Y, et al. Robust safe control for nonlinear quadrotor with a cable-suspended payload systems via control barrier function and disturbance estimator[J]. Control Engineering Practice, 2025, 165: 106564.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001572483100001

Rotating 3D laser mapping system for Multi-rotor drones

Keywords

Unmanned aerial vehicle, Rotating 3D lidar, Position estimation, Environment perception

Abstract

Accurate positional estimation is an essential prerequisite for the regular operation of an autonomous rotary-wing unmanned aerial vehicle (UAV). However, the field of view (FOV) limitation problem of lidar makes it more challenging to locate the rotary-wing UAV in an unknown environment. To address rotor drones with an insufficient FOV and the observation blindness of lidar in complex environments, this paper designs a rotorcraft UAV system based on rotating 3D lidar and proposes a simultaneous localization and mapping algorithm for rotating 3D lidar. The algorithm distinguishes between planar and edge features based on the curvature value of the point cloud firstly. Then to reduce the impact caused by the UAV motion and lidar rotation, messages about inertial measurement unit (IMU) and real-time rotation angle are used to compensate for these motions twice while the IMU measurements are used for state prediction, and the error-sate iterative extended Kalman filter is used to update the residuals after matching line and surface features with sub-map. Finally, Smoother high-rate odometer data was obtained through IMU pre-integration and first-order low pass filter. The experimental results show that the proposed rotating lidar unit in indoor and outdoor conditions makes the rotorcraft UAV have a larger FOV, which not only improves the environmental perception capability and positional estimation accuracy of the rotorcraft, but enhances the positioning reliability and flight stability of the rotorcraft UAV in complex environments.

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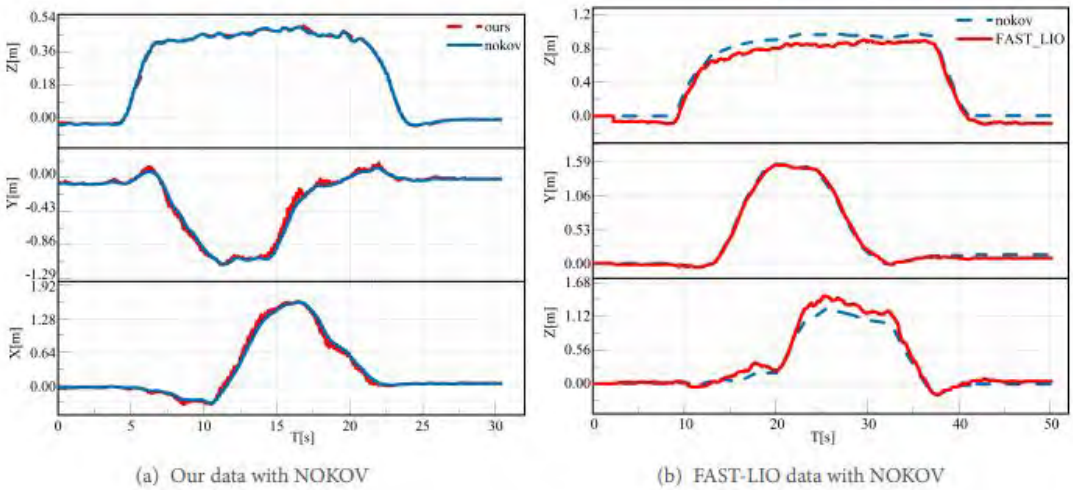

(a) Our data with NOKOV (b) FAST-LIO data with NOKOV

Figure 8. Comparison of ground-truth location data.

How NOKOV Contributes to the Research

The rectangular motion was performed under the indoor motion capture system, and the displacement x-axis, y-axis, and z-axis output results of the rotating 3D laser SLAM odometer, fixed-angle FAST-LIO, androtating FAST-LIO (Ours, F-FAST-LIO, R-FAST-LIO) were compared with the positioning results (Nokov) ofthe motion capture system, respectively, as inFigure 8Aand B.

Citation Fu M, Zhang H, Wang S, et al. Rotating 3D laser mapping system for multi-rotor drones[C]//2023 2nd International Conference on Robotics, Artificial Intelligence and Intelligent Control (RAIIC). IEEE, 2023: 1-6.

Link https://ieeexplore.ieee.org/abstract/document/10281055

RRT*ASV: Improved RRT* path planning method for Ackermann steering vehicles

Keywords

Path planning, RRT, Ackermann-steer vehicle, Sample based

Abstract

The path planning of the Ackermann steering vehicle needs to take into account the driving safety and following feasibility of the vehicle. Many path planners consider the feasibility of following a set of curvilinear paths using the maximum vehicle steering constraint. However, existing methods are usually limited by the accuracy of the meshing or the discontinuity of the route curvature, which makes vehicle path following control challenging. A sampling-based planner is proposed under the concept of a pre-existing road network model, along with an optimal path planning algorithm considering the motion constraints of Ackermann Steer Vehicles, named Rapidly-exploring Random Tree Star for Ackermann Steer Vehicles (RRTASV). Specifically, a weighted directed graph model of road networks is constructed by defining vertex rules and using the Dijkstra algorithm to generate a sequence of vertices from the starting point to the target point. On this basis, the Pure Pursuit (PP) algorithm is proposed to generate the arc path and give the direction to the new state point, the Dubins curve is used to complete the rewiring, and the turning cost function is proposed to reduce the sharp turning path. The proposed algorithm was evaluated for performance in a simulation environment and validated for feasibility on a physical platform. The evaluation outcomes demonstrate that among various paths tracked by the Ackermann steering vehicle, the reference path generated by RRTASV exhibits the lowest lateral tracking error of 0.025 m, and significantly alleviates the controller load by at least 60.66% when compared to the baseline algorithms.

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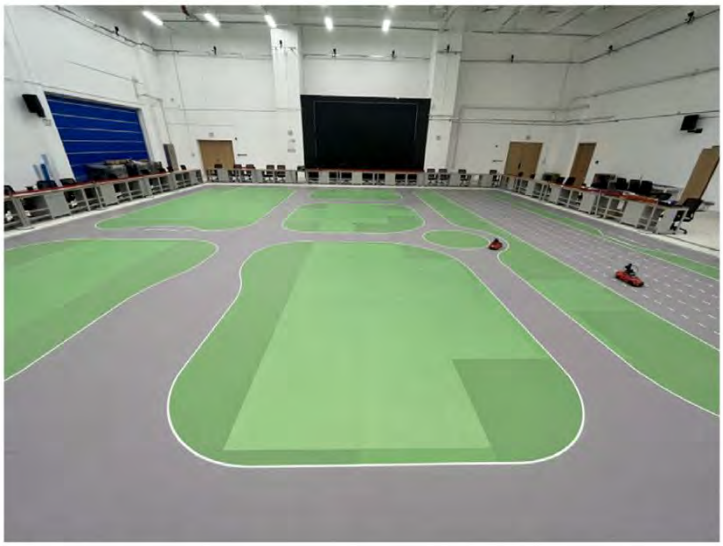

Fig. 14. Experimental map and vehicle scene. The map has a size of 16 m x 16 m. Green areas represent non-accessible zones, while gray areas represent accessible zones. The experimental vehicles are Ackermann steering vehicles.

How NOKOV Contributes to the Research

The platform is established using the ROS system, and the target point information is sent via UDP to the vehicle for path calculation and following. 24 infrared sensors from the NOKOV Motion Capture System were deployed for precise vehicle localization. An Ackermann steering mechanism is used on the experimental vehicle with a length of 0.4 m and a minimum turning radius of 1.0 m. The indoor high-precision positioning system is used for vehicle localization with millimeter-level accuracy. The experimental map is shown in Fig. 15.

Citation Lei C, Li J, Deng Y, et al. RRT ASV: Improved RRT path planning method for Ackermann steering vehicles[J]. Expert Systems with Applications, 2025, 279: 127349.

Link https://www.sciencedirect.com/science/article/abs/pii/S0957417425009716

Safe affine formation using terminal sliding mode control with input constraints

Abstract

Formation control is a fundamental task in the realm of autonomous multiagent systems. To drive a group of agents to maneuver continuously with the desired formation, this paper studies the finite-time affine formation control problem with disturbances, input constraints and safety guarantee. A non-singular terminal sliding mode control (NTSMC) is implemented to achieve finite-time convergence of all followers to their desired positions. Additionally, an auxiliary system is deployed to address input constraints resulting from the physical properties of the affine formation system. To mitigate the impact of lumped disturbances, a finite-time disturbance observer (FTDO) is employed to estimate the disturbances and compensate for their effects. Based on FTDO, the auxiliary system and the above NTSMC, a finite-time robust controller is developed as the nominal controller. By modifying the nominal controllers to comply with safety constraints, control barrier functions are employed to ensure the safety of the formation system in obstacle-filled environment. Finally, the effectiveness and feasibility of this method are validated through simulations and real-world experiments.

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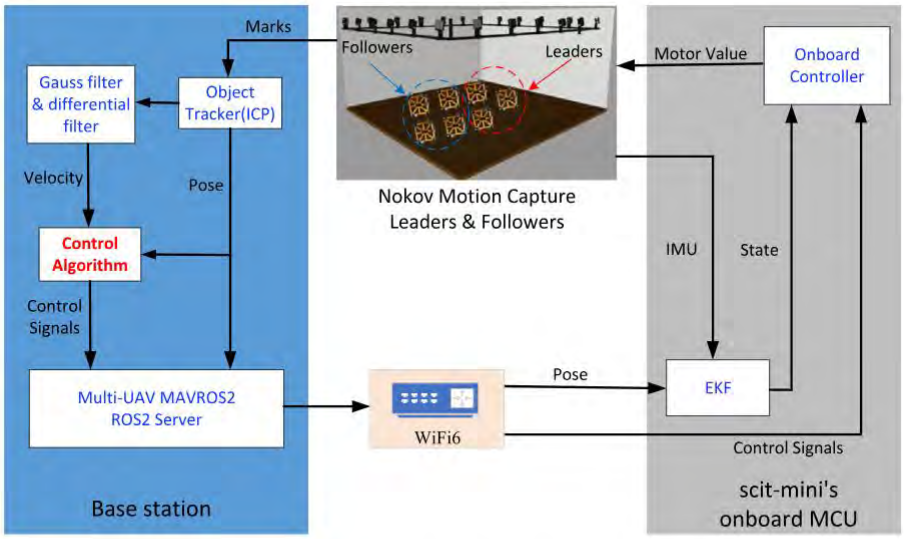

FIGURE 11 System framework in experiment.

How NOKOV Contributes to the Research

To validate the simulation results and ensure the practicaapplicability of the proposed control method, we conductedreal-world experiments on a physical system. The experimental setup replicated the dynamics of the simulated model. We conduct the experiment on a group of nano-quadcopters namedscit-minis (as shown in Figures 2 and 11)under the supervision of a NOKOV motion capture system. Compared with thewell-known nano-quadcopter crazyfile2.0 \[41], our quadcopterscit-mini has much power and longer battery life. Meanwhile,we used an open-source, unmanned vehicle Autopilot SoftwareSuite called ArduPilot to make it easier to transfer the algo.rithm from simulation to the real world.

Citation Liu B, Wang Z, Wang C, et al. Safe affine formation using terminal sliding mode control with input constraints[J]. IET Control Theory & Applications, 2024, 18(12): 1597-1608.

Link https://onlinelibrary.wiley.com/doi/10.1049/cth2.12692

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Safe Formation Control For Micro-UAV Using Control Barrier Functions

Keywords

Micro-UAV formation, super-twisting sliding mode control, safe formation control

Abstract

The formation control for unmanned aerial vehicles (UAVs) has become a key research focus in the past two decades. This paper studies the issues of formation tracking and safety control for micro-UAV swarms. A distributed finite-time formation control method based on an adaptive super-twisting algorithm is designed, ensuring that micro- UAVs can quickly converge to the desired formation within a finite time. Meanwhile, a safety formation control method based on control barrier functions is developed to address collision and obstacle avoidance during formation maintenance. The effectiveness and superiority of the proposed methods are validated through both simulation and real-world micro-UAV experiments in obstacle environments.

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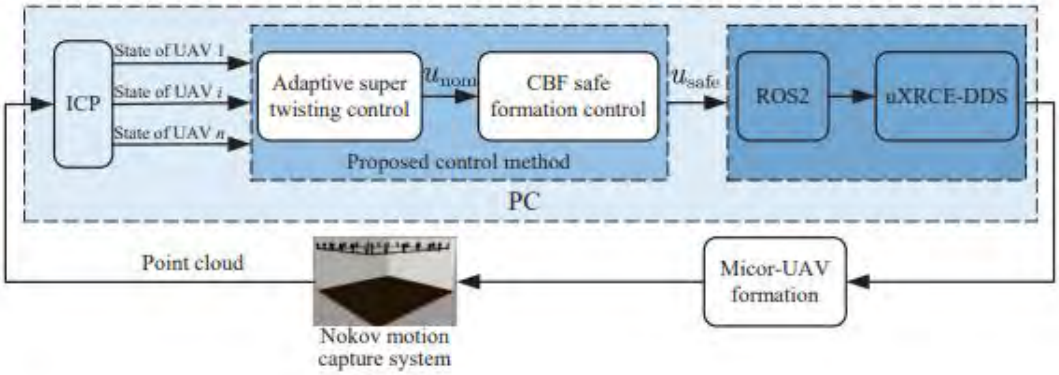

Fig. 6. System framework for experiment.

How NOKOV Contributes to the Research

The architecture of the experimental system is shown in Fig.6. We conducted the experiments using a group of nano-quadcopters, referred as scit-minis, under the supervision of a NOKOV motion capture system. Due to space limitations,please refer to \[14] for a detail of the experimental system.The results of the experiment is shown in Fig.7-9.

Citation Liu B, Yang S, Li Q, et al. Safe Formation Control For Micro-UAV Using Control Barrier Functions[C]//2024 China Automation Congress (CAC). IEEE, 2024: 3933-3938.

Link https://ieeexplore.ieee.org/abstract/document/10864752

Saturated Output Feedback Control for Quadrotor Trajectory Tracking Via Fixed-Time Observers

Keywords

Quadrotor output feed, backfixed-time observer, differential flatness, disturbance rejectionreal-time experiments

Abstract

In this paper, a saturated output feedback trajectory tracking scheme for a quadrotor is developed via the fixed-time observer (FxTO) technique. The translational controller is investigated based on a saturated nonlinear control law, where the unmeasurable velocity states are estimated by the FxTO. The proposed FxTO theoretically guarantees the convergence of the estimation error in a fixed time, and the stability of closed-loop system is proved. Then a cascaded attitude controller is investigated, and a feedforward compensation is introduced via differential flatness approach. Moreover, a fixed-time disturbance observer (FxTDO) is introduced to improve the robustness against disturbances. Finally, the tracking accuracy and robustness of the proposed method are verified via simulations and experiments.

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Figure 4: The structure diagram of experimental platform.

How NOKOV Contributes to the Research

The structure diagram of experimental platform is shown in Fig. 4. The control computations are performed using on-board STM32F407VG microcontroller at 100 Hz and 250 Hz for position and attitude control, respectively. The attitude measurements are obtained from an on-board ICM20602 IMU module. The position measurements are obtained from the Nokov motion capture system equipped with eight infrared cameras, and then sent to the quadrotor via WiFi in real time.

Citation Xia Y, Gong M, Ma D, et al. Saturated output feedback control for quadrotor trajectory tracking via fixed-time observers[J]. Control Engineering Practice, 2026, 168: 106713.

Link https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5152049

Self-Attention Factor Graph Neural Network for Multiagent Collaborative Target Tracking

Keywords

Collaborative tracking, factor graph, factor graph neural network,vgraph neural network (GNN), multiagent network

Abstract

Collaborative target tracking is an essential task in positioning systems, particularly in environments characterized by high dynamics, multisource heterogeneous data, and interactive multiagent scenarios. The challenge in such networks lies in the direct utilization of multisource heterogeneous data as feature input for models. Additionally, the presence of high-dynamic time-series data complicates the extraction of dependencies by the models. To address these issues, we introduce a novel approach that integrates a factor graph-based data fusion method with a graph neural network. This combination is designed to uncover potential dependencies between time-series data and positional information within dynamic networks. Furthermore, we employ a self-attention mechanism, enabling distance-agnostic autonomous selection of complex network features. This innovation allows the model to achieve enhanced accuracy performance while simultaneously reducing computational costs. We validated our approach through simulation experiments. The results demonstrated the method's effectiveness in fusing and selecting multisource heterogeneous information within collaborative networks. It also excelled in identifying potential relationships between feature information and positional data, showcasing the robustness and applicability of our proposed solution in challenging collaborative target tracking environments.

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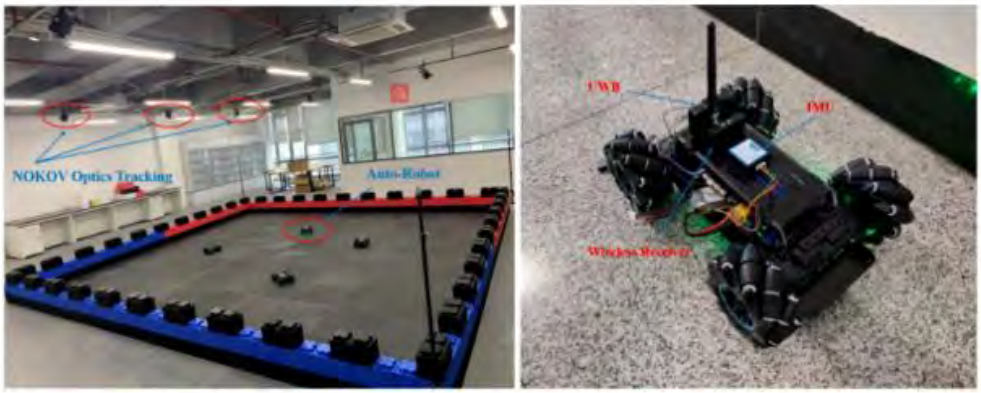

Fig. 11. (a) Scene for physical experiment. (b) Auto-robot and sensors used for the test.

How NOKOV Contributes to the Research

In the physical experiment, we set up four auto-robotsequipped with UWB and IMU sensors in a 10 m × 10 mfield, as shown in Fig.11. The robots were allowed to movein random walk motion, and their sensor information and position data were collected during the experiments. The ground-truth positions were captured using the NOKOV opticsmotion tracking system\[50]. We evaluated the algorithm's performance based on the trajectory paths and localization errors of the agents.

Citation Xu C, Su R, Wang R, et al. Self-Attention Factor Graph Neural Network for Multiagent Collaborative Target Tracking[J]. IEEE Internet of Things Journal, 2024, 11(20): 32381-32392.

Link https://ieeexplore.ieee.org/abstract/document/10445748

Self-immunity study of quadrotor UAV based on Modelica system modeling and disturbance feed-forward compensation

Abstract

For addressing the challenges of decreased attitude and trajectory tracking accuracy and a delayed response in the flight control operations of quadcopter unmanned aerial vehicles (UAVs) under the uncertainties of model parameters and external disturbances, this study leverages the advantages of the non-causal declarative modeling language Modelica in system modeling and simulation. In addition, it incorporates the nonlinear Active Disturbance Rejection Control (ADRC) framework for disturbance observation, estimation, and compensation. A state observer is designed to mitigate the impact of external disturbances and model uncertainties through feed-forward compensation, and stability analysis is conducted. Numerical simulations for hover resistance demonstrate that, compared to the cascade proportional integral differential (PID) control strategy, PID-NLADRC reduces the maximum deviation induced by wind disturbances by ~50% and shortens the disturbance influence time by around 40%. Simulations for different trajectories, such as planar or spatial, smooth or abrupt changes, indicate that under the PID-NLADRC control strategy, the real-time spatial distance deviation mean is reduced by 69.5%, and the peak time is shortened by 75.7%. Validation through multi-objective applications and physical experiments highlights the advantages of PID-NLADRC in terms of positioning accuracy, rapid tracking, and disturbance suppression, aligning well with the fast, precise, and robust flight control requirements of quadcopter UAVs.

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How NOKOV Contributes to the Research

The test environment and software interface are shown inFig. 24. As shown, the NOKOV optical 3D motion capture system is sed to accurately capture the position, attitude, velocity, and accel-eration data of the quadcopter UAV, and the above data are analyzedand processed to generate the real-time position parameters of theUAV. According to the real-timemotion parameters provided by the NOKOV motion capture system, the time distribution curves of the position components of thex-channel andy-channel under the cascade PID, as well as the PID-NLADRC control strategies, are plotted, respectively, in Figs. 25 and26.

Citation Xiaopeng B, Zhou H, Tan S. Self-immunity study of quadrotor UAV based on Modelica system modeling and disturbance feed-forward compensation[J]. AIP Advances, 2024, 14(7).

Link https://www.semanticscholar.org/paper/Self-immunity-study-of-quadrotor-UAV-based-on-and-Bao-Zhou/5da5f879a4c008b54976656a977a768375982ac2

Self-organized multi-target trapping of swarm robots with density-based interaction

Keywords

Swarm robots, Distributed robot systems, Multi-target trapping, Self-organized trapping, Density-based interaction

Abstract

The task of multi-target trapping in swarm robots can often be solved by global shape planning and target assignment, but it still remains a challenge to achieve fully self-organized multi-target trapping behavior based on local information. In this paper, inspired by the concept of spatial density in physics and biology, we proposed a novel density-based method to enable the swarm robots to entrap multiple targets with either single-ring, multi-ring or multi-subgroup formation in a distributed and self-organized way while neither communication among robots nor encirclement function is required. Each robot's local spatial density is considered as the main clue for the individual's motion decision-making and the enclosed configurations emerge from such individual-level interactions rather than being explicitly designed. Numerical simulations and real robotic experiments are conducted to validate the effectiveness of the proposed method. The results show that the proposed self-organized trapping method allows a swarm of robots to entrap multiple moving targets in a stable, flexible, noise-tolerate and size-scalable fashion.

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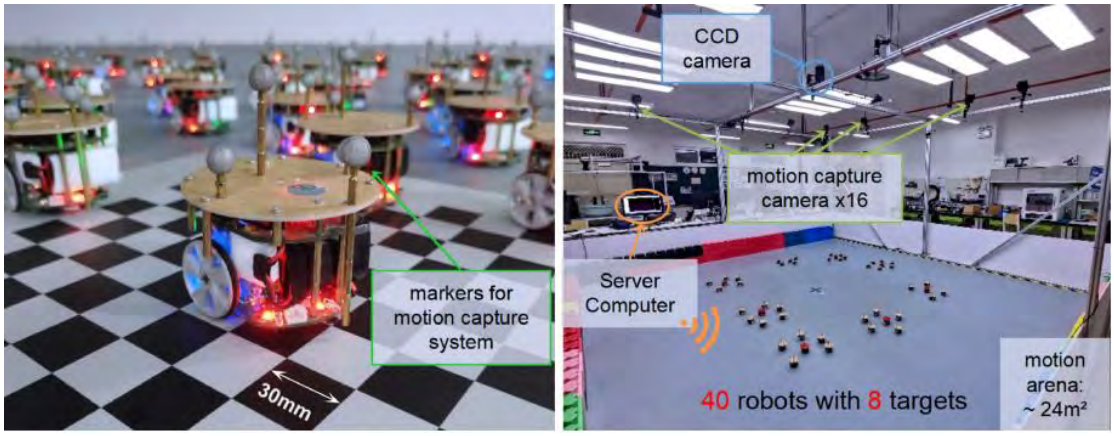

How NOKOV Contributes to the Research

We employed a motion capture system manufactured by NOKOV to track the positions and headings of all robots.

Citation Lei X, Zhang S, Xiang Y, et al. Self-organized multi-target trapping of swarm robots with density-based interaction[J]. Complex & Intelligent Systems, 2023, 9(5): 5135-5155.

Link https://link.springer.com/article/10.1007/s40747-023-01014-6

Self-Organized Patchy Target Searching and Collecting with Heterogeneous Swarm Robots Based on Density Interactions

Keywords

Heterogeneous swarm robots; Target search; Target collection; Targets with patchy distribution; Shrinking strategy; Density interaction

Abstract

The issue of searching and collecting targets with patchy distribution in an unknown environment is a challenging task for multiple or swarm robots because the targets are unevenly dispersed in space, which makes the traditional solutions based on the idea of path planning and full spatial coverage very inefficient and time consuming. In this paper, by employing a novel framework of spatial-density-field-based interactions, a collective searching and collecting algorithm for heterogeneous swarm robots is proposed to solve the challenging issue in a self-organized manner. In our robotic system, two types of swarm robots, i.e., the searching robots and the collecting robots, are included. To start with, the searching robots conduct an environment exploration by means of formation movement with Levy flights; when the targets are detected by the searching robots, they spontaneously form a ring-shaped envelope to estimate the spatial distribution of targets. Then, a single robot is selected from the group to enter the patch and locates at the patch's center to act as a guiding beacon. Subsequently, the collecting robots are recruited by the guiding beacon to gather the patch targets; they first form a ring-shaped envelope around the target patch and then push the scattered targets inward by using a spiral shrinking strategy; in this way, all targets eventually are stacked near the center of the target patch. With the cooperation of the searching robots and the collecting robots, our heterogeneous robotic system can operate autonomously as a coordinated group to complete the task of collecting targets in an unknown environment. Numerical simulations and real swarm robot experiments (up to 20 robots are used) show that the proposed algorithm is feasible and effective, and it can be extended to search and collect different types of targets with patchy distribution.

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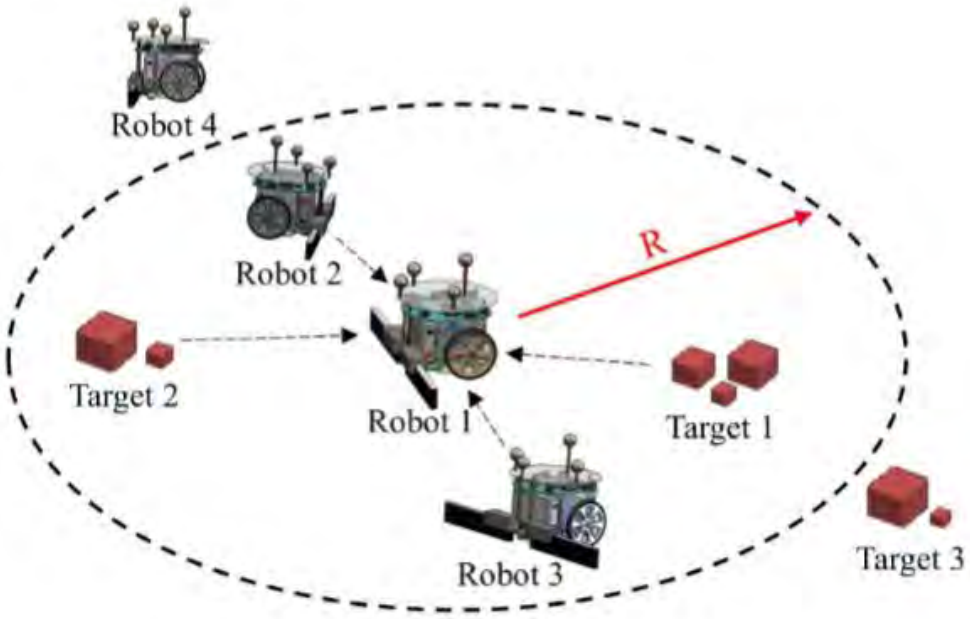

How NOKOV Contributes to the Research

In our experiments, the robot's position, speed, and heading are captured in real time by the NOKOV moving capture system. The real-time position of target units is collected by a top-view camera. Note that although this information is collected globally, the control of each robot only uses the local information within its sensing range.

Citation Xiang, Y.; Lei, X.; Duan, Z.; Dong, F.; Gao, Y. Self-Organized Patchy Target Searching and Collecting with Heterogeneous Swarm Robots Based on Density Interactions. Electronics 2023, 12, 2588. https://doi.org/10.3390/electronics12122588

Link https://www.mdpi.com/2079-9292/12/12/2588

Self-Organized Reynolds Swarms of Unmanned Aerial Vehicles in Dense Environments

Keywords

self-organized swarm, UAV, collision avoidance

Abstract

The achievement of fully distributed self-organized swarm control of unmanned aerial vehicles (UAVs) in realistic environments is a current challenge in the field of UAV research. This paper investigates the problem of self-organized swarm control of UAVs in dense environ ments. Based on the behavioral characteristics of biological swarms, a distributed self-organizing Reynolds (SOR) swarm model is proposed to improve the environmental adaptability of UAV swarms. In order to evaluate the performance of the SOR swarm in actual deployment, the proposed SOR swarm method is validated in a real indoor environ ment based on the Nokov motion capture system using five quadrotor UAVs, and the autonomous navigation of the UAV swarm in an obstacle environment, similar to the flocking behavior of a bird, is successfully achieved.

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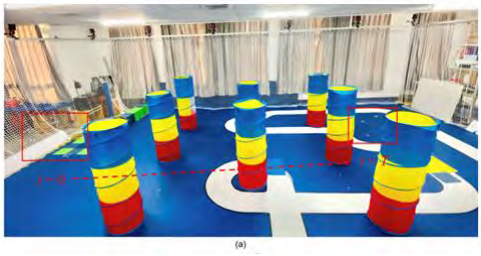

(a)

How NOKOV Contributes to the Research

This paper builds a self-organized UAV swarm flight experiment platform, which mainly consists of a Nokov 3D optical motion capture system, a ground control station equipped with a robot operating system (ROS), and a Crazyswarm \[23] UAV platform (see Fig.1).

Citation Ding, Y., Xiong, H., Shi, X., Liu, J., Chen, Y., Wang, J. (2025). Self-organized Reynolds Swarms of Unmanned Aerial Vehicles in Dense Environments. In: Yan, L., Duan, H., Deng, Y. (eds) Advances in Guidance, Navigation and Control. ICGNC 2024. Lecture Notes in Electrical Engineering, vol 1352. Springer, Singapore. https://doi.org/10.1007/978-981-96-2260-3_34

Link https://link.springer.com/chapter/10.1007/978-981-96-2260-3_34#citeas

Self-organized swarm robot for multi-target trapping based on self-regulated density interaction

Keywords

Swarm robots, Distributed robot systems, Multi-target trapping, Self-organized trapping, Density-based interaction

Abstract

In swarm robotics, multi-target trapping usually relies on global information or explicit communication, posing a challenge for robots to autonomously self-organize and trap multiple targets with only local perceptual data. We present a self-regulated density-based approach for self-organized multi-target trapping. This method employs density-based negative feedback control and density-distance weighted target selection. Our approach leverages distributed perception, where robots perceive nearby peers within their sensory range, eliminating the need for explicit information exchange and enabling autonomous trapping. During task execution, negative feedback control adjusts swarm density, ensuring it reaches an optimal level. Building on this, individual robots use density fields and relative target positions to select suitable targets, achieving self-regulated dispersed selection and multi-target trapping. We validate our approach through numerical simulations and real-world robot experiments. Results demonstrate stable self-organization, efficient self-regulated dispersed target selection, and successful target trapping, even with a limited number of trapping robots in low-redundancy scenarios.

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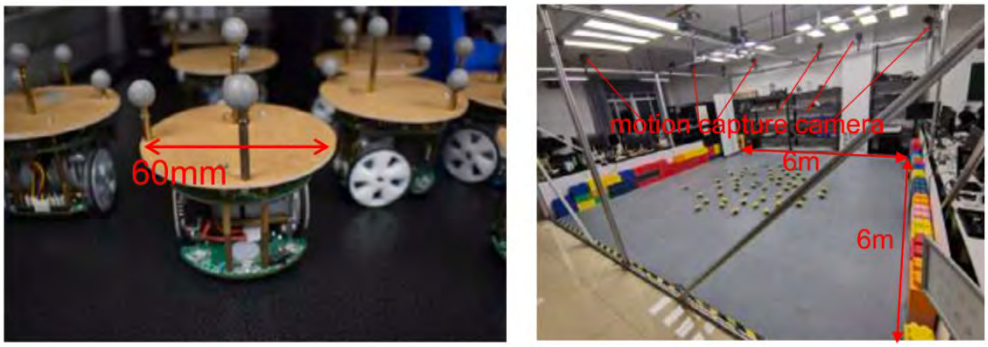

Fig. 14. SwarmBang robot and the observe tracking system.

How NOKOV Contributes to the Research

For tracking the positions and orientations of all robots, a motion capture system by NOKOV was employed. Global information was disseminated to all robots through a custom communication protocol utilizing a 2.4G RF module. Each individual robot then made its own decisions based on the localized information obtained from the global message.

Citation Zhou Y, Tao Y, Lei X, et al. Self-organized swarm robot for multi-target trapping based on self-regulated density interaction[J]. Information Sciences, 2024, 661: 120119.

Link https://www.sciencedirect.com/science/article/abs/pii/S002002552400032X

Semi-autonomous Hybrid UGV-UAV System for Search and Rescue Missions

Keywords

Semi-autonomous • Hybrid system • UGV • UAV • Search and rescue • Machine learning • Disaster response

Abstract

The proposed system is a new semi-autonomous hybrid system of UGVs and UAVs that could ultimately prove to be improvements over search and rescue missions in challenging environments. One important payback is realized that the benefits between both systems are synergistic: UAVs serve for aerial reconnaissance by gaining their bird's eye view and carry out a physical involvement with the object by using the terrestrial functionalities of UGV's. A number of autonomous operations such as obstacle avoidance and identification of the target, and the planning of the path will be considered with implementing them into an incredibly sophisticated and complex machine learning algorithm. Moreover, the architecture must include a reliable and robust communication network, which allows for real-time transfer of indispensable data directly from the vehicle to the ground control station. The hybrid system runs a wide range of simulations to evaluate and test its efficiency and effectiveness in various scenarios, from not only complex topographies but also difficult meteorological conditions that may have an impact on its performance. The results of such simulations are totally understood by the operations team that will lead to improvements in efficiencies, in developed safety measures, and operational coverage made considerably easier for all relevant stakeholders.

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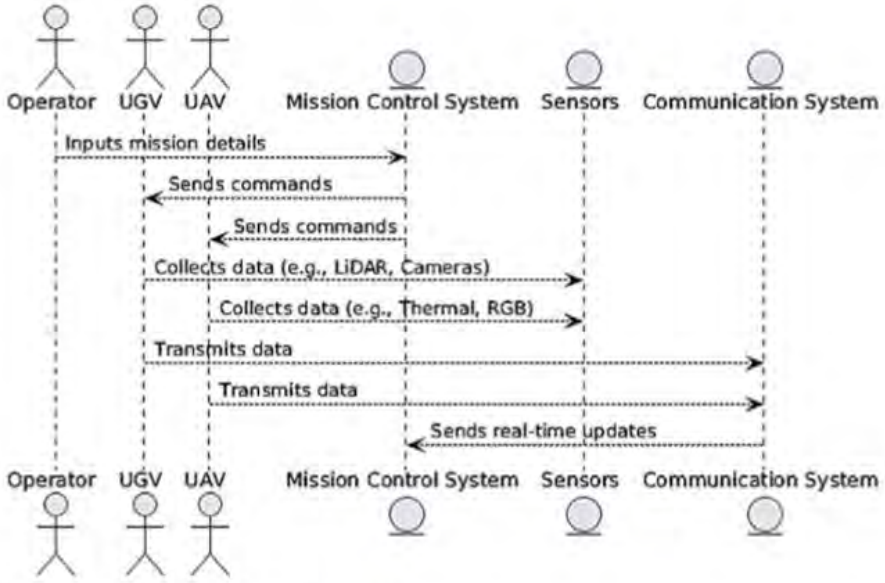

Fig. 4 Architecture diagram of UAV-UGV

How NOKOV Contributes to the Research

We use a specially prepared experimental platform that makes use of the NOKOV motion capture in combination with the Gazebo simulator. The ROS-Simulink information bridge does allow users to focus on the design of control algorithms, once they would be experimenting with experimental data. An optimization algorithm was used in determining the optimal sizing of a PV/wind/battery hybrid system to ensure continuous electricity supply in rural areas \[21]. On the other hand, incorporation of EVs into radial distribution systems (RDSs) poses challenges regarding power losses and voltage stability \[22].

Citation John De Britto C, Jothi Sri R, Sandhiya V. Semi-autonomous Hybrid UGV-UAV System for Search and Rescue Missions[C]//International Conference on Universal Threats in Expert Applications and Solutions. Singapore: Springer Nature Singapore, 2025: 359-374.

Link

https://ev.publinks.top/app/doc/?docid=cpx_469f3d8c19a6d5ecfd7M797510178165218&pageSize=25&index=1&searchId=8df287136d37492eb9e821bdd8b95298&resultsCount=2&usageZone=resultslist&usageOrigin=searchresults&searchType=Quick

Shape-Adaptive Planning and Control for a Deformable Quadrotor

Abstract

Drones have become essential in various applications, but conventional quadrotors face limitations in confined spaces and complex tasks. Deformable drones, which can adapt their shape in real-time, offer a promising solution to overcome these challenges, while also enhancing maneuverability and enabling novel tasks like object grasping. This paper presents a novel approach to autonomous motion planning and control for deformable quadrotors. We introduce a shape-adaptive trajectory planner that incorporates deformation dynamics into path generation, using a scalable kinodynamic A\ search to handle deformation parameters in complex environments. The backend spatio-temporal optimization is capable of generating optimally smooth trajectories that incorporate shape deformation. Additionally, we propose an enhanced control strategy that compensates for external forces and torque disturbances, achieving a 37.3% reduction in trajectory tracking error compared to our previous work. Our approach is validated through simulations and real-world experiments, demonstrating its effectiveness in narrow-gap traversal and multi-modal deformable tasks.

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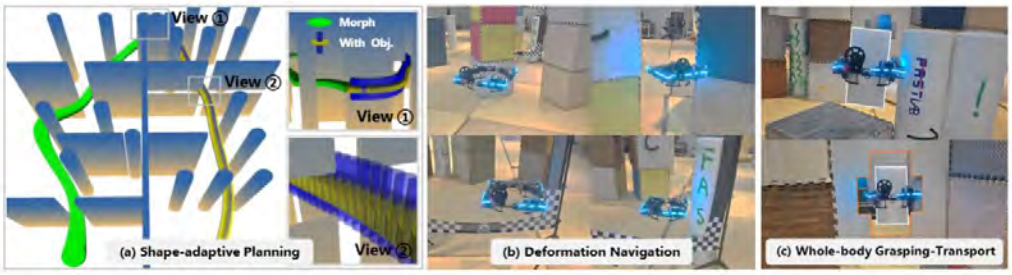

Fig. 1: (a) Shape-adaptive motion planning for deformable traversal and whole-body grasping-transport. (b) Highlight of autonomous deformation enabling traversal through confined areas. (c) Highlight of autonomous grasping-transport through a narrow cross-shaped gap.

How NOKOV Contributes to the Research

We conduct simulations and real-world experiments to validate the effectiveness of the proposed algorithms. The simulations are all conducted in a Linux environment on a computer equipped with an Intel Core i7-10700 CPU. The real-world experiments utilize our optimized morphing and grasping integrated quadrotor as the experimental platform. In addition to the planning and control modules, we use a radar to construct an environmental point cloud map as environmental input, and fuse data from a NOKOV Motion Capture System and an IMU to obtain the motion states.

Citation Y. Wu et al., "Shape-Adaptive Planning and Control for a Deformable Quadrotor," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 21197-21204, doi: 10.1109/IROS60139.2025.11245898.

Link https://ieeexplore.ieee.org/document/11245898

Sharing Traffic Priorities via Cyber–Physical–Social Intelligence: A Lane-Free Autonomous Intersection Management Method in Metaverse

Abstract

Replacing traffic signals with roadside vehicle-to-infrastructure systems in the era of connected and autonomous vehicles (CAVs) is promising. Managing CAVs in a signal-free intersection, known as autonomous intersection management (AIM), controls the driving behavior of each intersection-traverse CAV to maximize the throughput. Although AIM improves the gross throughput, the fairness of each individual vehicle in its right of way is not seriously considered. This study sets up an AIM system in the cyber–physical–social space to trade traverse priorities quantitatively and fairly. To that end, one needs an AIM method that is optimal and stable, otherwise no convincing trades of traverse priorities could be made. This study proposes a near-optimal lane-free AIM method based on numerical optimal control, wherein log-exp functions are deployed to convexify nondifferentiable collision-avoidance constraints. Besides that, a parameterized social force model (SFM) is proposed to provide a tunable initial guess for numerical optimal control. By tuning the urgency weights in SFM, one may get cooperative trajectories in different homotopy classes, which are further utilized to decide the amount of virtual currency to reward those CAVs who tend to share their traverse priorities. The overall method improves the traverse throughput with individual fairness respected. In experiencing this system, passengers learn how to behave with politeness when they drive manually. Experiments show the efficiency and robustness of the AIM method and also show the efficacy of the overall priority-sharing system.

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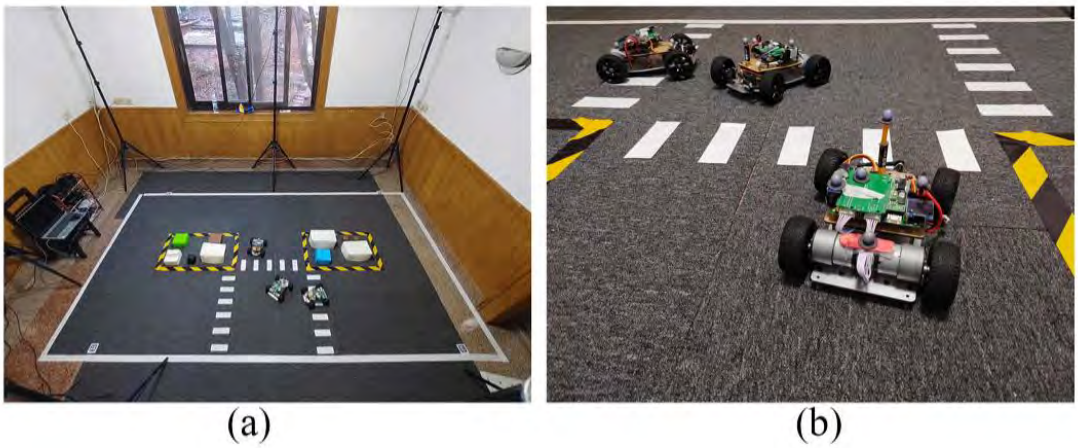

Fig. 8. Set up of indoor field experiments: (a) field layout of a T-junction scenario and (b) reflective marking points on tops of each robot for localization.

How NOKOV Contributes to the Research

Six infrared sensors of NOKOV Motion Capture System were set up for CAV localization. Specifically, reflective marking points were uniquely placed on the top of each car-like robot \[Fig. 8(b)]. The reflective marking points reflected the beams emitted from the six light sources before the reflected beams got captured by the infrared sensors. Through this, the position of a robot can be estimated.

Citation B. Li et al., "Sharing Traffic Priorities via Cyber–Physical–Social Intelligence: A Lane-Free Autonomous Intersection Management Method in Metaverse," in IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 53, no. 4, pp. 2025-2036, April 2023, doi: 10.1109/TSMC.2022.3225250.

Link https://ieeexplore.ieee.org/document/9982626

Simultaneous Time Synchronization and Mutual Localization for Multi-robot System

Keywords

Geometry, Pipelines, Planning, Computational efficiency, Collision avoidance, Robots, Trajectory optimization

Abstract

Mutual localization stands as a foundational component within various domains of multi-robot systems. Nevertheless, in relative pose estimation, time synchronization is usually underappreciated and rarely addressed, although it significantly influences estimation accuracy. In this paper, we introduce time synchronization into mutual localization to recover the time offset and relative poses between robots simultaneously.

Under a constant velocity assumption in a short time, we fuse time offset estimation with our previous bearing-based mutual localization by a novel error representation.

Based on the error model, we formulate a joint optimization problem and utilize semi-definite relaxation (SDR) to furnish a lossless relaxation. By solving the relaxed problem, time synchronization and relative pose estimation can be achieved when time drift between robots is limited. To enhance the application range of time offset estimation, we further propose an iterative method to recover the time offset from coarse to fine.

Comparisons between the proposed method and the existing ones through extensive simulation tests present prominent benefits of time synchronization on mutual localization. Moreover, real-world experiments are conducted to show the practicality and robustness.

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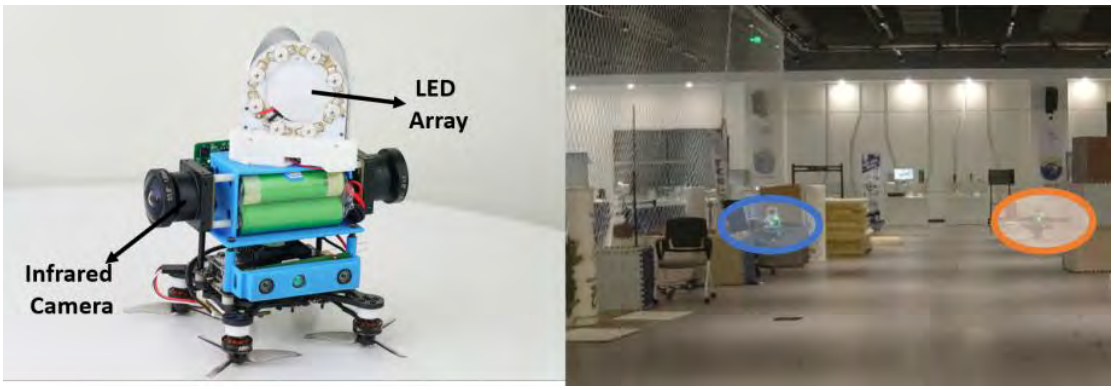

How NOKOV Contributes to the Research

We conducted totally five experiments with different trajectory patterns, including pentagons, figure-eight, and squares. In each experiment, we fix the time offset between trajectories as 1s and utilize motion capture as the ground truth.

Citation Wen X, Wang Y, Zheng X, et al. Simultaneous Time Synchronization and Mutual Localization for Multi-robot System[C]//2024 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2024: 2603-2609.

Link https://ieeexplore.ieee.org/abstract/document/10610915

Spatial-temporal constrained particle filter for cooperative target tracking

Keywords

Cooperative target tracking; Accumulative error; Particle filter; Error ellipse resampling ; Spatial temporal constraints

Abstract

Localization is one of the most important topics of cyber physical system. In the last decades, much attention has been paid to the precise localization and performance evaluation in wireless sensor networks. Inertial-measurement-unit and Time-of-Arrival fusion is a state-of-the-art method to solve the accumulative error and drifting problem faced by sole inertial-measurement-unit positioning and navigation. Network cooperative technology could effectively suppress the accumulative error. This paper presents a spatial-temporal constrained particle filter algorithm for cooperative target tracking, so as to solve the problem of multi-target high-precision position tracking in complex and highly dynamic environments. Firstly, we propose an error-ellipse-resampling particle filter method. In the resampling stage of the particle filter, error ellipses with different confidence probabilities would be established with the use of the known estimated center and confidence scale, to achieve hierarchical resampling optimization based on the geometrical position of particles. As for cooperative tracking, an optimization method of state estimation based on spatial distance constraint is proposed, so that the Bayesian filter can benefit from spatial information and achieve cooperative tracking of spatial-temporal information fusion. Numerical experimental results show that the proposed error-ellipse-resampling particle filter could decrease the growth rate of cumulative errors and reach a positioning accuracy of 1.05 m, multi-target cooperative error-ellipse-resampling particle filter can effectively eliminate the cumulative error and achieve a positioning accuracy of 0.24 m.

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How NOKOV Contributes to the Research

To verify the effectiveness, practical experiments are conducted to compare the proposed method with above-mentioned state-of-the-art methods. A total of 10 navigation robots are programmed to travel randomly by applying the collision-avoidance algorithm (Thrun, 2002), and each robot maintains a distance-ranging frequency of once a second with its neighboring nodes. A high precision optical motion tracking system (Mars 2H) (https://www.nokov.com/en/, 2020) is deployed so as to provide the ground truth measurements. Considering the size of the tracking target and the deployment requirements of optical devices, an open filed covered 10 m10 m is chosen as a testing scenario.

Citation Xu C, Wang X, Duan S, et al. Spatial-temporal constrained particle filter for cooperative target tracking[J]. Journal of network and computer applications, 2021, 176: 102913.

Link https://www.sciencedirect.com/science/article/abs/pii/S1084804520303726

Stabilizing Angle Rigid Formations with Prescribed Orientation and Scale

Keywords

Bearing measurement; formation control; multi-agent systems; prescribed orientation and scale;

Abstract

Angle rigid formations have the advantage of requiring only bearing measurements in their implementation. However, the capability of controlling the orientation and scale of these formations has not been explored. This undetermined orientation and scale can degrade the robustness of the formation against measurement noise. To maintain both advantages of requiring less sensor measurements and sustaining robustness against measurement noise, this paper aims to achieve a desired angle rigid formation while simultaneously controlling its orientation and scale. We first design a formation algorithm for the first three agents to achieve a desired triangular formation with prescribed orientation and scale. Using the control gain design technique, we then design formation control algorithms for the remaining agents such that the overall desired formation can be achieved under a vertex addition operation. We present the role of generic property from angle rigidity for the formation's stability analysis. We also highlight that with one additional relative position measurement or two additional communication channels, the local convergence to the desired formation can be improved to a global convergence. Experiments are conducted to validate the theoretical results and the advantages are highlighted in comparison with other two formation control laws.

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How NOKOV Contributes to the Research

In this section, we validate the results of Theorems 1-4 using four wheeled robots to achieve a desired rectangular formation. The size of each robot is 60cm length, 46cm width, and 46cm height. Each robot has four wheels and is controlled by an on-board computer. Since wheeled robots are unicycles, we apply feedback linearization [20], [21] towards a reference point that is inside of the robot to obtain the single-integrator dynamics (1). The measurements of relative positions or bearings among robots are captured by the NOKOV Mocap system sampling at the rate of 120 Hz. Each robot will calculate the control input along its X-axis and Y-axis according to the designed controllers, then apply it to the robots.

Citation Chen L, Yang Q, Shi M, et al. Stabilizing angle rigid formations with prescribed orientation and scale[J]. IEEE Transactions on Industrial Electronics, 2021, 69(11): 11654-11664.

Link https://ieeexplore.ieee.org/abstract/document/9583880

Stackelberg-Game-Based Defense Analysis Against Advanced Persistent Threats on Cloud Control System

Keywords

Advanced persistent threats (APTs), cloud control system (CCS), security as a service, Stackelberg game

Abstract

In this paper, the security problem for a cloud control system (CCS) is studied. In the CCS, so-called advanced persistent threats (APTs) can be launched by a malicious attacker to reduce the quality of service of cloud and deteriorate the system performance further. To defend against APTs and create a security as a service scheme, a defender needs to allocate defense resource to different units serving to different plants for improving the overall system performance when the CCS accommodates multiple physical plants simultaneously. After observing the defender's action, the attacker decides which serve units to comprise. Considering that both defender and attacker are subject to resource constraints, the interaction of two sides is modeled by a Stackelberg game. The optimal solutions for two players under different types of budget constraints are investigated. Simulation examples and comparison results are provided to verify the main results of this paper.

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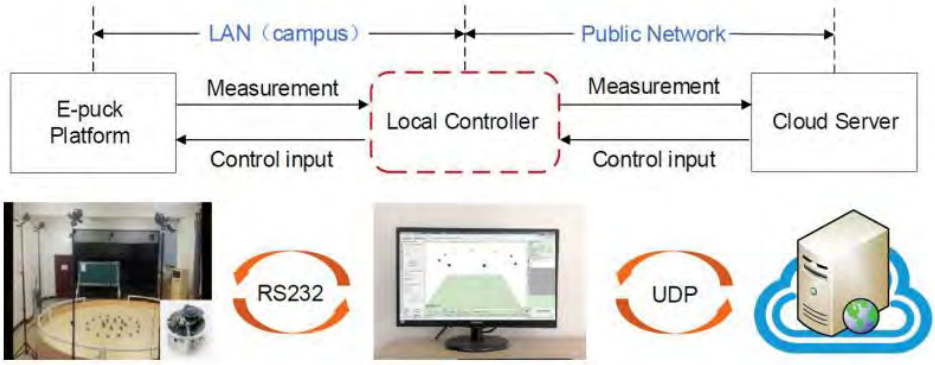

Fig. 6. CCS platform.

How NOKOV Contributes to the Research

To further illustrate the validity and applicability, the proposed scheme is applied to a platform of CCS, which consists of E-puck wheeled mobile robots, a Nokov motion capture system (NMCS), a local controller and a cloud server shown in Fig. 6. The NMCS is equipped with eight cameras to provide real time localization of E-pucks. The cloud server provides service for time delay tolerant system performance that needs to deal with a large amount of data. The local controller receives commands from cloud server and sends them to Epucks. Meanwhile, the local controller can also provide realtime control service.

Citation Yuan H, Xia Y, Zhang J, et al. Stackelberg-game-based defense analysis against advanced persistent threats on cloud control system[J]. IEEE Transactions on Industrial Informatics, 2019, 16(3): 1571-1580.

Link https://ieeexplore.ieee.org/abstract/document/8746251

Stereo Visual Inertial Mapping Algorithm for Autonomous Mobile Robot

Keywords

Visual inertial mapping; Stereo camera; AMR; SLAM

Abstract

Simultaneous Localization and Mapping (SLAM) is a fundamental problem for autonomous mobile robots (AMRs). AMRs are widely used in automated warehousing, factory material transfer systems, flexible assembly systems, and other intelligent transportation sites. The visual Inertial Odometry (VIO) which consists of the camera and inertial-measurement-unit (IMU), is a popular approach to achieve accurate 6-DOF state estimation. However, such locally accurate VIO is prone to drift and cannot provide a global consistent map. The prerequisite for re-localizing the robot and ensuring precise autonomous navigation is an accurate and global consistent map of its environment. In this study, we propose a stereo visual-inertial mapping system. The front-end is a robust stereo VIO based on a tightly-coupled sliding window optimization. The core of the back-end is the global Bundle-Adjustment (BA) which is a nonlinear optimization, in which IMU is also added as a time-domain constraint. Meanwhile, stereo-camera-IMU extrinsic calibration is performed in BA to improve mapping accuracy. The selection principles of keyframes and map points are also designed according to the AMRs application characteristics. Further, the forward and backward Perspective-n-Point (PNP) method is also adopted to avoid the loop-detection mismatch. The performance of the system was validated and compared against other state-of-the-art algorithms. The findings revealed the effectiveness and robustness of this stereo visual-inertial mapping algorithm.

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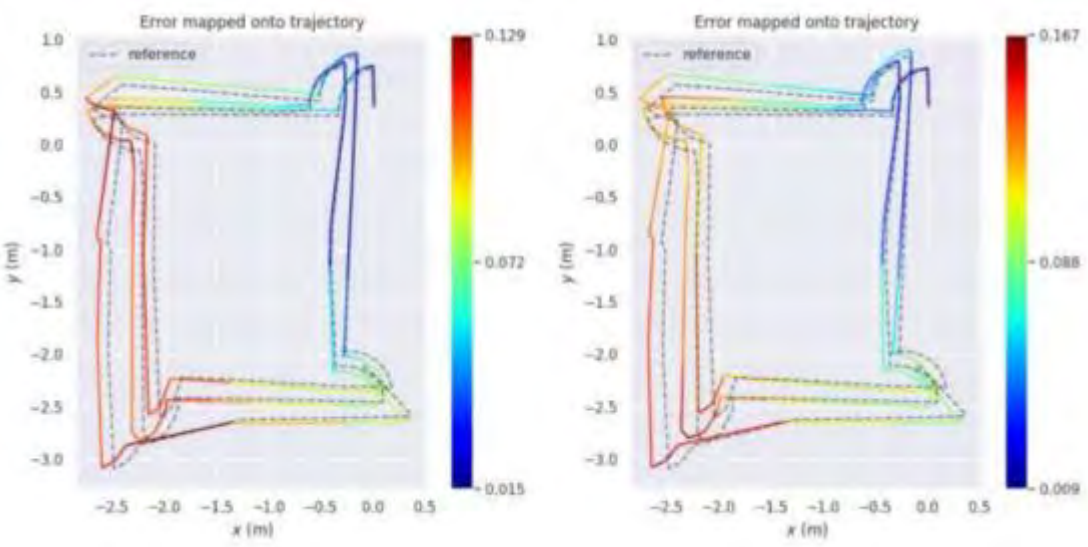

How NOKOV Contributes to the Research

The algorithm is verified by comparing two different scenes: one is a small-scale laboratory scene and the other is a large-scale scene (≥1000 square meters). A motion capture system (NokovMars1.3H) is a physically-based ground truth in laboratory scenes. In a large-scale scene, the surrounding environment is not friendly to visual SLAM, which contains pedestrians, a long corridor, low-light condition, textureless area, glass, and reflection. In this experiment, we compare our algorithm with another state- of-the-art algorithm VINS- Fusion \[36]. For a fair comparison, most config parameters of both our algorithm and VINS-Fusion are similar.

Citation Zhang M, Han S, Wang S, et al. Stereo visual inertial mapping algorithm for autonomous mobile robot[C]//2020 3rd International Conference on Intelligent Robotic and Control Engineering (IRCE). IEEE, 2020: 97-104.

Link https://ieeexplore.ieee.org/abstract/document/9199252

Swift Pursuer: A Topology-accelerated and Robust Approach for Pursuing an Evader in Obstacle Environments with State Measurement Uncertainty

Keywords

Multi-robot systems, path planning for multiple mobile robots or agents, task and motion planning, constrained control, surveillance robotic systems

Abstract

This letter presents a topology-accelerated and robust pursuit framework for environments with obstacles considering state measurement uncertainty. Our framework consists of three primary components: the selection of virtual target points using topological heuristic method to encourage path diversity, the computation of safe pursuit regions based on Voronoi cell (VC) and the solution of an adaptive robust path controller based on Control Barrier Function (CBF) to guarantee safety under state measurement uncertainty. Topological heuristics broadly capture the topological structure of the environment and provide guidance for the selection of target points for each pursuer. Then the chance constrained obstacle-aware Voronoi cell (CCOVC) for each pursuer is constructed by calculating separation hyperplane and buffer terms. Finally, we formulate chance CBF and chance Control Lyapunov Function (CLF) constraints based on CCOVC, using convex approximation to determine their upper bounds. We then find the adaptive robust path controller by solving a Quadratically Constrained Quadratic Program (QCQP). Benchmark simulation and experimental results demonstrate the efficiency and robustness of the proposed framework.

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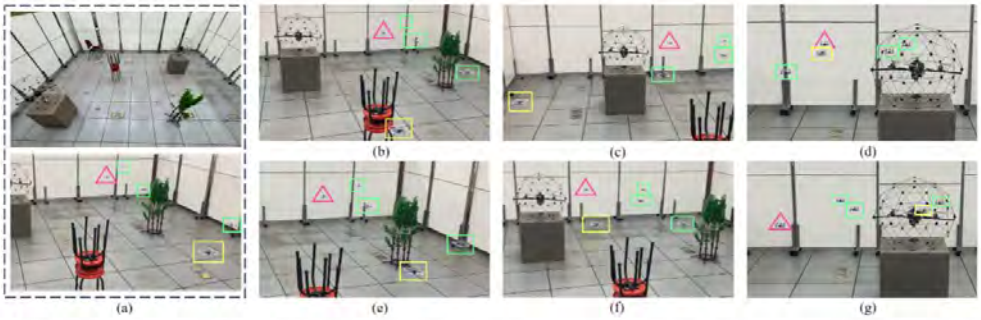

Fig. 9. Four pursuers, denoted as green and yellow squares, are chasing a evader marked by a pink triangle. (a) The experimental environment and initial positions. (b)-(d) Screenshots from the pursuit experiment with the proposed framework. (e)-(g) Screenshots from the pursuit experiment using the proposed framework but without incorporating the proposed virtual target generation method. Video is available at https://youtu.be/dMraLDrzh3A.

How NOKOV Contributes to the Research

The poses of the UAVs captured by the motion capture system (NOKOV) are utilized as the ground-truth value and,based on this, the Gaussian noises are manually added togenerate noisy measurements. The CCOVC and control inputsare calculated on the host workstation and then transmittedover a local area network to drive the movement of each UAV.Fig. 9 displays screenshots from the experimental process. Theproposed method successfully captures the evader at20.8swhereas not using the virtual target generation method allowsthe evader to escape. This can be observed by comparing the movement of the UAV marked by yellow rectangles.

Citation Rao K, Yan H, Huang Z, et al. Swift pursuer: A topology-accelerated and robust approach for pursuing an evader in obstacle environments with state measurement uncertainty[J]. IEEE Robotics and Automation Letters, 2025.

Link https://ieeexplore.ieee.org/abstract/document/10908058

Symmetry-Guided Multi-Agent Inverse Reinforcement Learning

Abstract

In robotic systems, the performance of reinforcement learning depends on the rationality of predefined reward functions. However, manually designed reward functions often lead to policy failures due to inaccuracies. Inverse Reinforcement Learning (IRL) addresses this problem by inferring implicit reward functions from expert demonstrations. Nevertheless, existing methods rely heavily on large amounts of expert demonstrations to accurately recover the reward function. The high cost of collecting expert demonstrations in robotic applications, particularly in multi-robot systems, severely hinders the practical deployment of IRL. Consequently, improving sample efficiency has emerged as a critical challenge in multi-agent inverse reinforcement learning (MIRL). Inspired by the symmetry inherent in multi-agent systems, this work theoretically demonstrates that leveraging symmetry enables the recovery of more accurate reward functions. Building upon this insight, we propose a universal framework that integrates symmetry into existing multi-agent adversarial IRL algorithms, thereby significantly enhancing sample efficiency. Experimental results from multiple challenging tasks have demonstrated the effectiveness of this framework. Further validation in physical multi-robot systems has shown the practicality of our method.

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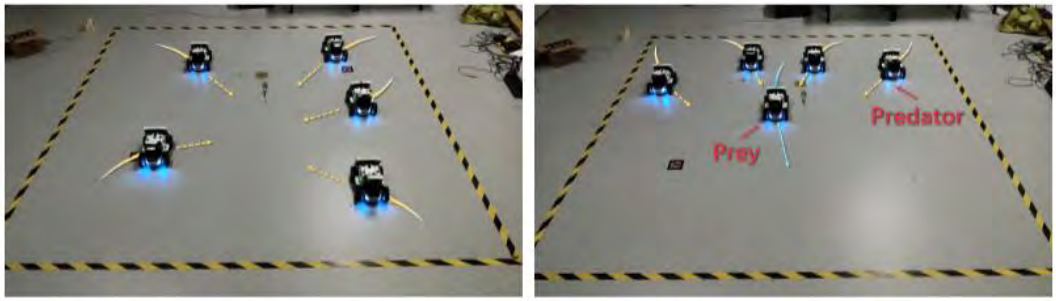

(a) Rendezvous. (b) Pursuit.

Fig. 6: Demonstration of the real-world scenarios.

How NOKOV Contributes to the Research

In this section, we deploy our algorithms in real-world environments to validate the effectiveness of SGF. Since Vicsek uses periodic boundary conditions that cannot be implemented in the real world, we focus on the other tasks instead. Specifically, we use Limo robots as agents, controlled via the Robot Operating System (ROS) system, with real-time environmental states captured by Nokov motion capture system. The setup of the task is shown in Fig. 6. The Rendezvous involves 5 agents, while the Pursuit consists of 4 predators and 1 prey. Without loss of generality, we choose MA-AIRL and S-MA-AIRL for real-world validation, using cumulative distance as the performance metric. The results, as presented in Table III, show that the algorithms using SGF complete tasks faster in both tasks, confirming the effectiveness of our method in real-world applications.

Citation Y. Tian, Y. Qi, X. Yu, W. Wu and J. Luo, "Symmetry-Guided Multi-Agent Inverse Reinforcement Learning," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 7989-7996, doi: 10.1109/IROS60139.2025.11246087.

Link https://ieeexplore.ieee.org/document/11246087

TALKER: A Task-Activated Language Model Based Knowledge-Extension Reasoning System

Keywords

AI-enabled robotics, autonomous systems, large language models, reinforcement learning, task planning

Abstract

Training drones to execute complex collective tasks via multi-agent reinforcement learning presents significant challenges. To address these challenges, this letter introduces the Task-Activated Language model-based Knowledge-Extension Reasoning system. Specifically, we trained drones in two fine-grained skills and developed an action primitive library based on these capabilities, enabling a hierarchical approach to managing complex swarm operations. Leveraging this primitive library, we employ large language models to perform task planning, continuously refining the planning outcomes based on external user feedback. Successful task codes are temporarily stored within the action primitive library, with their utilization being authorized based on internal feedback from maintainers. We defined this process as knowledge expansion. In addition, more refined customized prompts are generated based on task descriptions and the action primitive documentation, a mechanism referred to as Task Activation. Our system synergistically integrates task activation and knowledge expansion mechanisms, enabling continuous evolution through human feedback to effectively manage extensive swarms in the execution of complex collective tasks. Experimental results demonstrate the superior performance of our system in various drone swarm tasks, including collaborative search, object tracking, cooperative interception, and aerial patrol.

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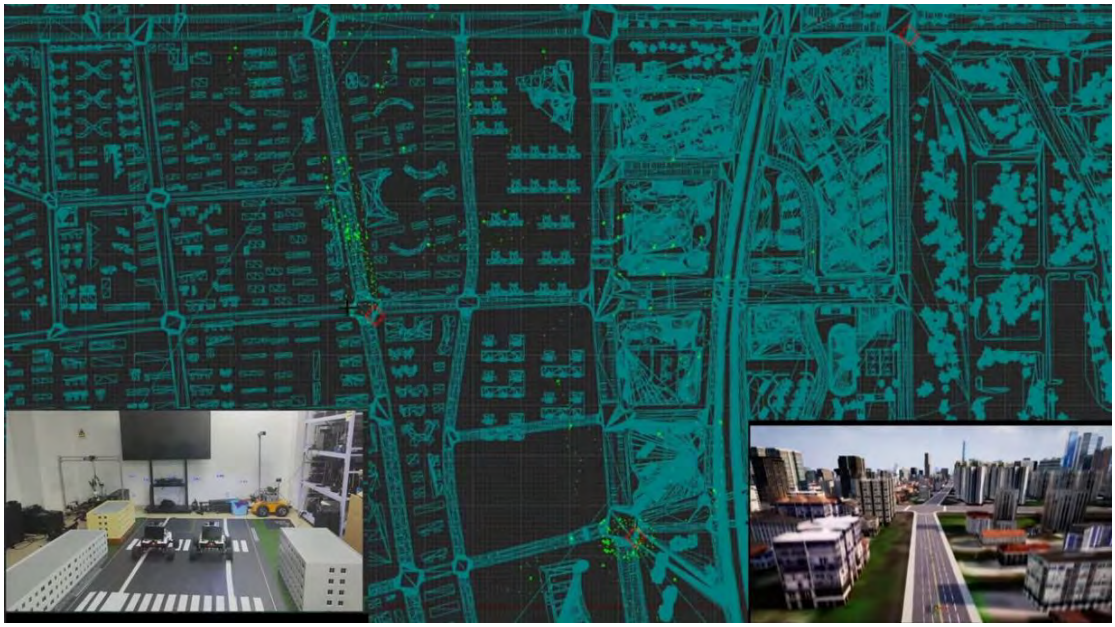

How NOKOV Contributes to the Research

Each task was executed 20 times, and the average results for each task are presented in Table III, and avideo demonstration of the AT6 task performed using TALKER is available in the supplementary materials. In addition, we have deployed some drones in the real world using a combination of virtual and physical integration. We used Crazyflies\[26]for this deployment, and indoor positioning is provided by the NOKOV motion capture system.

Citation Lou J, Shi R, Lin Y, et al. Talker: A task-activated language model based knowledge-extension reasoning system[J]. IEEE Robotics and Automation Letters, 2024.

Link https://ieeexplore.ieee.org/abstract/document/10776775

Task Optimization for a Class of Mobile Depth Sensor Network in Unknown Environments

Keywords

Depth sensor network, Luus–Jaakola (LJ) algorithm, the guaranteed coverage

Abstract

This article proposes an optimization based on guaranteed coverage to address the challenge of continuously optimizing the mobile depth sensor network online due to the insufficient information captured in an unknown environment. In this optimization framework, the coverage set representing the coverage area of the depth sensor is introduced. A novel concept of the guaranteed coverage set of depth sensor is proposed, which is a subset of the coverage set. The proposed guaranteed coverage set, plays a crucial role in addressing measurement noises and enabling proper selection of dithers in optimization algorithms to stay within the coverage area. By utilizing the Luus–Jaakola (LJ) algorithm, the optimal pose for each depth sensor in the mobile network is determined. This takes into account the task-relevant cost function at every time instant. This algorithm ensures that the chosen poses effectively optimize the overall performance of the network. A method for the selection of the parameters in the proposed algorithm is also presented. The proposed optimization is then applied to a path planning case with obstacle avoidance, and a simultaneous mapping and coverage case, using stereo cameras as the depth sensors. Simulation and experiment results verify the effectiveness of the optimization for mobile depth sensor network in unknown environment.

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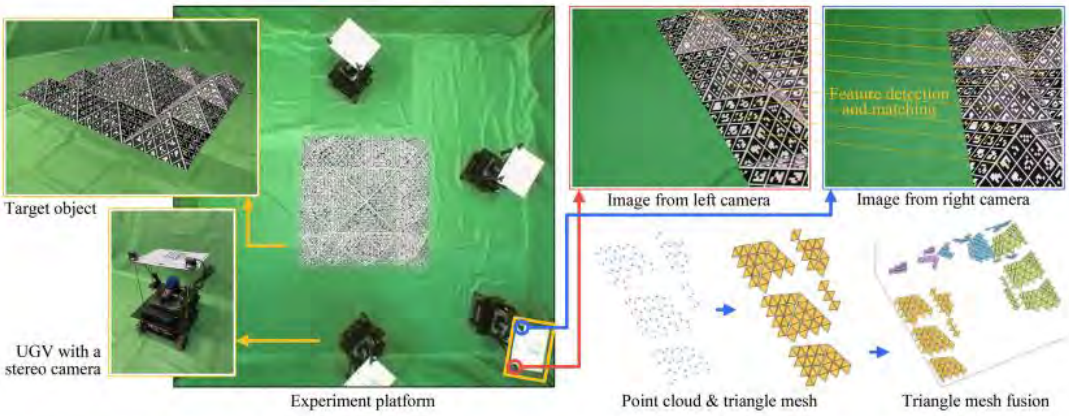

Fig. 8. UGVs, experiment platform, and an example of mapping in experiment.

How NOKOV Contributes to the Research

The UGV is equipped with an NVIDIA JetsonTX2, which is responsible for receiving image data input sand performing calculations, subsequently outputting control signals to the motors. The stereo camera is composed of two JRWT DW800 cameras. The intrinsic parameters of the stereo camera are shown in Table II, and the length of the baseline isdp=100 mm, the yaw angles are set as αl=αr=90◦.The extrinsic parameters of the stereo camera are obtained through the motion capture system from NOKOV.

Citation Lei Z, Chen X, Tan Y, et al. Task Optimization for a Class of Mobile Depth Sensor Network in Unknown Environments[J]. IEEE/ASME Transactions on Mechatronics, 2024, 30(1): 286-297.

Link https://ieeexplore.ieee.org/abstract/document/10506109/

Theory and experiment on distributed output formation tracking of unmanned aerial and ground vehicle swarm systems over jointly connected digraphs

Keywords

Swarm systems, Formation tracking, Unmanned aerial vehicle (UAV), Unmanned ground vehicle (UGV), Switching topology

Abstract

This paper studies the distributed output formation tracking control problem of the unmanned aerial vehicle (UAV) and unmanned ground vehicle (UGV) swarm systems, where the UAV swarm cooperatively tracks the output trajectory of the UGV in a formation under directed jointly connected communication networks. A three-layer formation tracking protocol is proposed. Firstly, a novel distributed observer using neighbor interactions is designed for each UAV to estimate the states of the UGV with parameterized inputs over periodic jointly connected digraphs. Next, based on the observation result and output regulation theory, a virtual reference system that tracks the trajectory of the UGV in the desired formation is constructed to generate reference states for each UAV. Then based on the differential flatness of UAVs, a geometric controller is utilized for UAVs to track the reference states and form the formation. An algorithm to determine the gain matrices of the protocol is also presented while the convergence of the system is analyzed. Finally, an experiment platform with three quadrotor UAVs and one UGV is built. The effectiveness of the proposed protocol is validated both by the simulation and experiment.

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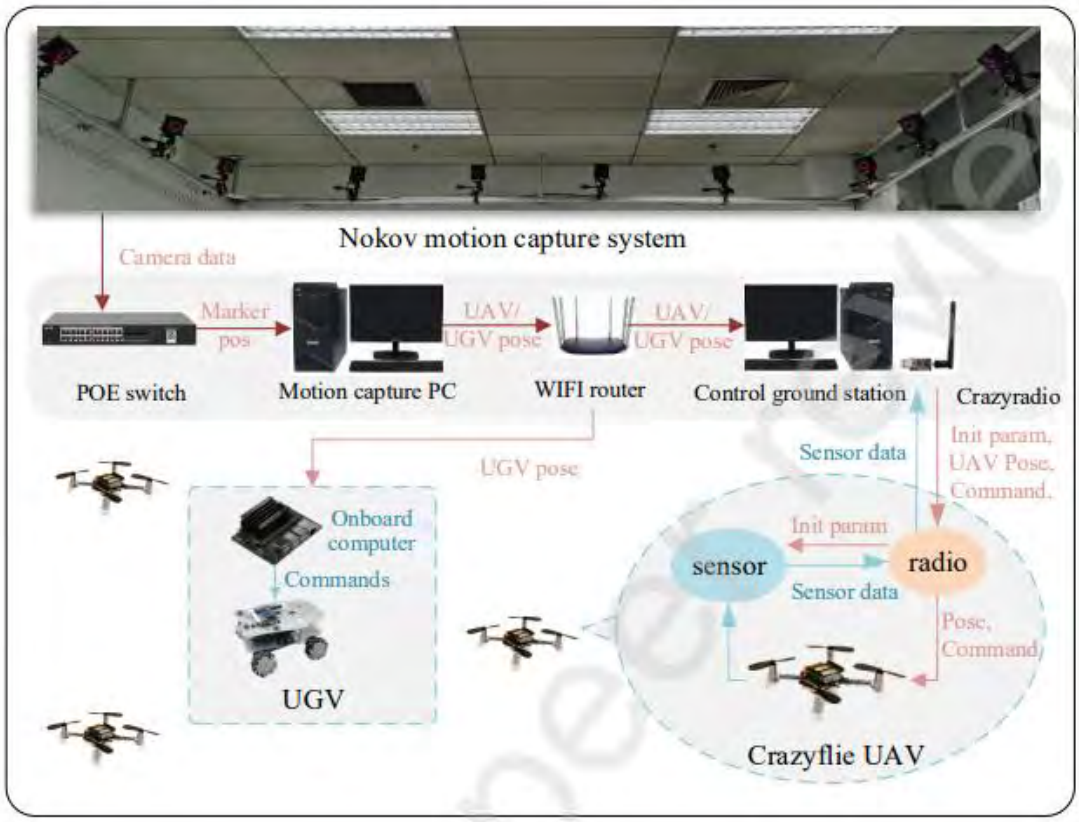

Figure 3: The framework of the experiment platform.

How NOKOV Contributes to the Research

In the experiment platform, each UAV and UGV is attached with fourrefective markers of different configurations. Twenty cameras are used in the Nokov motion capture system to detect the markers while a motion capture computer calculates the positions and attitudes of each vehicle at a frequency of 100 Hz and broadcasts them through the WiFi network. The UAVs in this platform are crazyfies of 32g and 92mm wheelbase.

Citation Shu P, Wang C, Hua Y, et al. Theory and experiment on distributed output formation tracking of unmanned aerial and ground vehicle swarm systems over jointly connected digraphs[J]. Control Engineering Practice, 2024, 152: 106070.

Link https://www.sciencedirect.com/science/article/abs/pii/S0967066124002296

Tight Fusion of Odometry, Kinematic Constraints,and UWB Ranging Systems for State Estimationof Integrated Aerial Platforms

Keywords

Odometry and localization, intergrated aerial platform, kinematic constraints, tight fusion

Abstract

Integrated Aerial Platforms (IAPs), consisting of multiple interconnected aircraft, offer a promising framework for aerial manipulation tasks by enhancing localization accuracy and reliability. Unlike aerial swarms, the interconnected nature of IAPs allows for exploiting physical constraints among aircraft to improve positioning and navigation systems. In this paper, we present an advanced decentralized multi-aircraft visual-inertial-range-physical odometry system that considers the position, velocity, and attitude constraints inherent to IAPs. By tightly fusing visual-inertial-range odometry and Ultra-Wideband (UWB) with kinematic constraints, we optimize odometry accuracy through the use of novel constraint-based methods. Our algorithm's performance is validated on simulated datasets and self-collected datasets, with flight experiments conducted on the IAP, demonstrating a significant improvement with a 28.7% reduction in drift over the baseline on real-world datasets and a 24.5% reduction on simulation datasets. Note to Practitioners—Motivated by the need for accurate localization in Integrated Aerial Platforms (IAPs), this paper introduces a novel approach to multi-aircraft odometry technology through the application of physical constraints. We propose a method that combines the physical constraints of IAPs with ranging data to achieve rapid and efficient unification of coordinate systems and precise estimation of anchor positions. We then develop a theoretical framework to analyze the position, velocity, and attitude constraints induced by the multiple aircraft within the IAP and introduce a decentralized optimization method to enhance odometry accuracy. This framework is referred to as Visual-Inertial-Range-Physical Odometry (VIRPO). Furthermore, using multiple self-collected datasets for IAPs, we conduct a thorough evaluation of the proposed VIRPO algorithm, comparing its performance with baseline methods. Test results show that VIRPO significantly improves localization accuracy. Finally, we implement the IAP platform and integrate the VIRPO algorithm to conduct flight experiments, verifying its effectiveness in real-world flight conditions. This marks the first time the VIRPO algorithm has been run onboard an actual IAP platform. In future research, we

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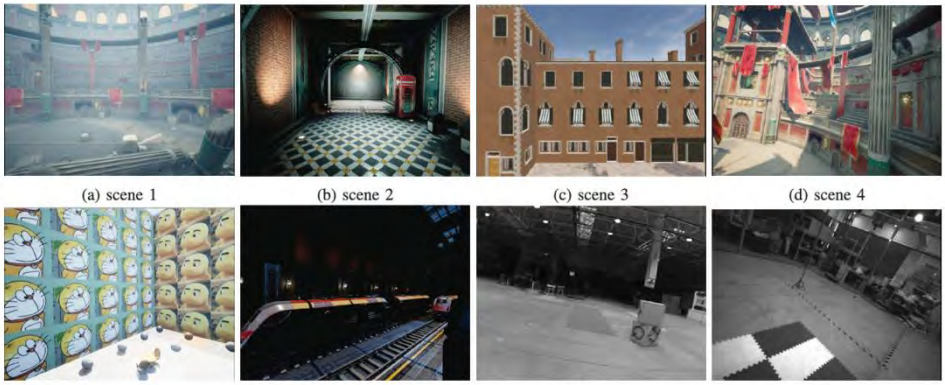
plan to explore more complex IAP configurations and additional types of constraints to further enhance the localization performance of IAPs.



(a) scene 1 (b) scene 2 (c) scene 3 (d) scene 4

(e) scene 5 (f) scene 6 (g) scene 7 (h) scene 8

Fig. 6. Figures (a) to (f) correspond to the scenarios from the unreal dataset, figure (g) represents the scenario from the handheld-ZED dataset, and figure (h) depicts the scenario from the handheld-realsense dataset.

How NOKOV Contributes to the Research

The Handheld-ZED dataset, lacking a physical UWB sensor, employed simulated UWB measure ments derived from ground truth provided by NOKOV motion capture system, while the Handheld-Realsense dataset featured a Linktrack P-B UWB sensor. The motion trajectory of the central platform during data collection is shown in Fig. 5a and Fig. 5b, and the corresponding motion scenarios are illustrated in Fig. 6g and Fig. 6h. During data collection, the operator moved freely while holding the device, including straight lines, turns, and vertical movements to simulate various flight patterns. The environment was an indoor lab space (approx imately 8m 6m) with some light occlusion from box and evenly distributed artificial lighting.

Citation Yu Y, Fan Y, Lai G, et al. Tight Fusion of Odometry, Kinematic Constraints, and UWB Ranging Systems for State Estimation of Integrated Aerial Platforms[J]. IEEE Transactions on Automation Science and Engineering, 2025.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001530295400029

Time-Varying Formation Planning and Distributed Control for Multiple UAVs in Clutter Environment

Keywords

Adaptive formation control, distributed coordination, multiple unmanned aerial vehicles (UAVs), obstacle avoidance

Abstract

In this article, we present a novel method to achieve optimization based obstacle avoidance and distributed regular polygon time-varying formation control for multiple unmanned aerial vehicle systems (UAVs) in clutter environment. Under a leader-following structure, directed communication graph is considered. The formation size is time-varying and the trajectory of the leader UAV is planned in real time. Different from most of the existing trajectory planning algorithms for single UAV, an optimization-based safe trajectory and formation size online planning algorithm are proposed. To deal with information loss caused by directed communication topology, distributed smooth adaptive filters are designed for each UAV to asymptotically estimate the safe trajectory and formation size. Besides, a geometric tracking controller is adopted to track the desired trajectory for each UAV. Experimental results are provided to demonstrate the effectiveness of the proposed method.

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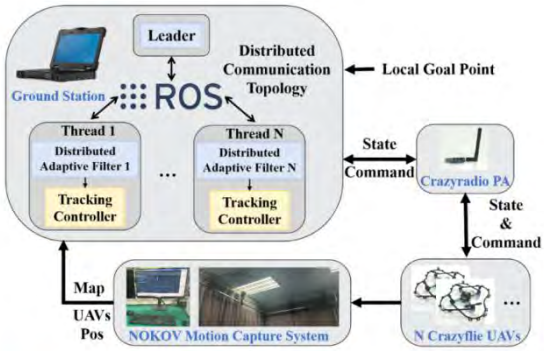

Fig. 3. Diagram of the experimental system.

How NOKOV Contributes to the Research

The NOKOV motion capture system obtains the markers' information on a PC and provides localization and obstacle sensing.

Citation K. Ze, W. Wang, K. Liu and J. Lü, "Time-Varying Formation Planning and Distributed Control for Multiple UAVs in Clutter Environment," in IEEE Transactions on Industrial Electronics, vol. 71, no. 9, pp. 11305-11315, Sept. 2024, doi: 10.1109/TIE.2023.3335448.

Link https://ieeexplore.ieee.org/document/10350055

Time-Varying Formation Tracking Control for Unmanned Aerial Vehicles with the Leader's Unknown Input and Obstacle Avoidance Theories and Applications

Keywords

formation tracking control, unmanned aerial vehicle (UAV), time-varying formation, collision avoidance, formation flying

Abstract

This paper investigates the time-varying formation tracking (TVFT) problems for unmanned aerial vehicle (UAV) swarm systems with the leader's unknown input and collision and obstacle avoidance mechanism. To solve the TVFT control problem which has not been studied extensively, distributed observers are proposed to estimate the leader's position and a TVFT control protocol is constructed. Stability of control protocol is proved by Lyapunov stability theory. Furthermore, the effectiveness of the TVFT control protocol is verified by numerical simulations and flying experiments, which is more convincing than the theoretical results only.

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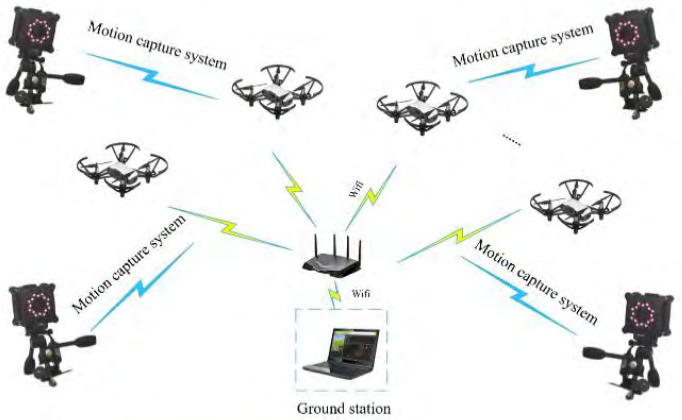

Figure 8. Hardware architecture of the experiment platform.

(a) Tello UAVs. **(b)** Motion capture system.

Figure 9. Formation tracking experimental platform.

How NOKOV Contributes to the Research

The main components of the experimental platform are shown in Figure 9, which include five Tello UAVs and the motion capture system. Each Tello quadrotor has an80 g ground weight with 6-cm tip-to-tip wingspan. The flight time of it is about 6–8 min.Because our algorithm is distributed, we need to use the relative distance of UAV rather than global information. The motion capture system provides the relative distance between UAVs by using optical cameras and subtracting the positions of the two drones. Each drone carries four marker balls to make sure that it can be captured by optical cameras. At the same time, the motion capture system calculates the position of the drone and transmits the results to the ground station. The outer loop for the trajectory in the XY plane is controlled by the formation tracking controller at a frequency of 100 Hz.

Citation Li Q, Hua Y, Dong X, Yu J, Ren Z. Time-Varying Formation Tracking Control for Unmanned Aerial Vehicles with the Leader's Unknown Input and Obstacle Avoidance: Theories and Applications. Electronics. 2022; 11(15):2334. https://doi.org/10.3390/electronics11152334

Link https://www.mdpi.com/2079-9292/11/15/2334

Time-varying group formation tracking for UAV swarm systems with collision avoidance

Keywords

UAV formation tracking, consensus method, artificial potential field collision avoidance, UAV experiment platform

Abstract

Aiming at the tracking and control problem of UAV swarm formation, it has important application value in civil fields such as environmental monitoring, disaster rescue, regional logistics Based on the consensus control theory, this paper proposes an unmanned aerial vehicle (UAV) group formation tracking control method with a collision avoidance mechanism. The designed control approach is verified on the Matlab simulation platform respectively. A physical verification is built by using motion capture as external positioning system, and the physical flight of the Tello UAV swam system is carried out. The results verify the effectiveness of the designed UAV group formation tracking control method with a collision avoidance mechanism.

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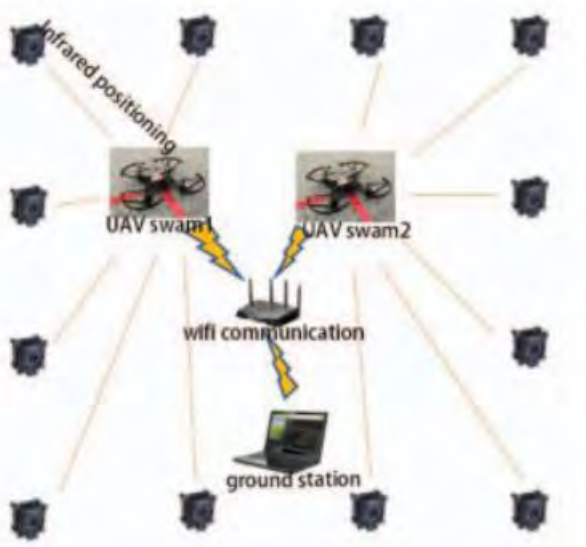

Fig. 5. Hardware architecture of the experiment platform

How NOKOV Contributes to the Research

The traditional UAV positioning relies on the GPS positioning system to obtain the real-time position of the satellite and the distance between each satellite and the object, and obtain the specific coordinates of the object through an algorithm. However, because the indoor GPS signal is not strong enough, the error is too large, and the size of the drone is less than ten centimeters, the GPS error in meters is unacceptable. After market research and comparison, I chose the motion capture system of NOKOV measurement company.

Citation Yu J, Hua Y, Yu J, et al. Time-varying group formation tracking for UAV swarm systems with collision avoidance[C]//2023 38th Youth Academic Annual Conference of Chinese Association of Automation (YAC). IEEE, 2023: 630-635.

Link https://ieeexplore.ieee.org/abstract/document/10401607

Towards Aerial Collaborative Stereo: Real-Time Cross-Camera Feature Association and Relative Pose Estimation for UAVs

Keywords

Collaborative robots, state estimation, visual feature association

Abstract

The collaborative unmanned aerial vehicles (UAVs) can construct a wide and variable baseline stereo camera, providing potential benefits in flexible and large-scale depth perception. Compared to the fixed-baseline stereo camera, the collaborative stereo system in dynamic flight face the additional challenge of continuously varying baselines, which necessitates real-time cross-camera stereo feature association and real-time relative pose estimation on resource-constrained onboard computers. To tackle these challenges, we propose a real-time dual-channel feature association with a guidance-prediction framework. This framework utilizes a graph neural network (GNN) to periodically guide cross-camera feature associations between two UAVs, while the guided features are continuously predicted to enable real-time feature association. Additionally, we propose a real-time relative multistate-constrained Kalman filter (Rel-MSCKF) algorithm, which efficiently integrates covisual overlapping features with the UAVs' visual-inertial odometry (VIO), enabling accurate and fast relative pose estimation. Extensive real-world experiments are performed using the widely adopted but resource-constrained NVIDIA NX onboard computer. The results demonstrate that the dual-channel algorithm achieves cross-camera feature association for 30 Hz image streams, with an average runtime of 14 ms, significantly outperforming the conventional cross-camera feature matching algorithms, which typically require over 70 ms. For the relative pose estimation of two cameras, the proposed Rel-MSCKF algorithm achieves pose estimation within 16 ms, outperforming the current pose-graph optimization (PGO) manner with 330 ms. Additionally, we examine the convergence behavior of Rel-MSCKF under various spatial configurations. The system's robustness is further evaluated under the challenges of asynchronous image acquisition, communication interruptions, and field-of-view (FOV) occlusions.

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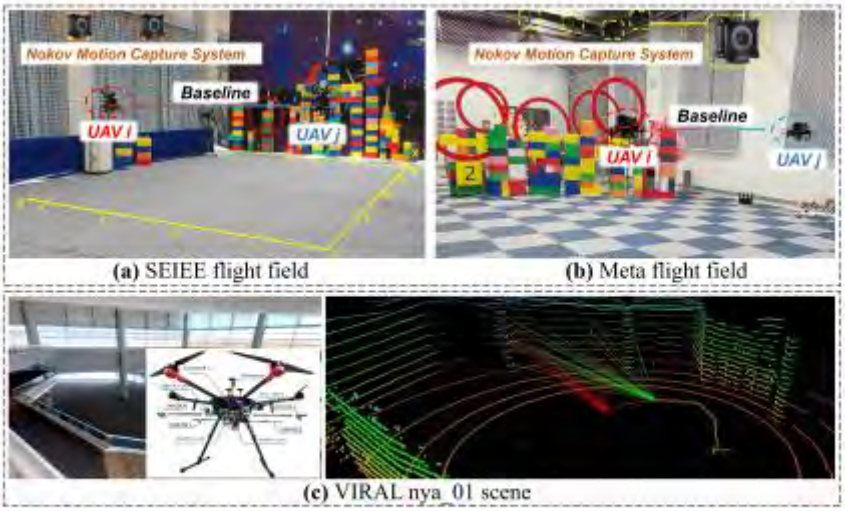

(a) SEIEE flight field (b) Meta flight field

(c) VIRAL nya_01 scene

Fig. 9. The flying experiments scenes for relative pose estimation. (a) shows the SEIEE flight field. (b) shows the Meta flight field. (c) shows nya_01 scene in VIRAL dataset.

How NOKOV Contributes to the Research

The real-world experiments are performed in the SEIEE flight field and the Meta flight field as shown in Fig.9 (a)(b).Both flight fields are equipped with the Nokov motion capture system to provide ground truth data for quantitative analysis.The Nokov system could provide position precision of 1 mmand an attitude precision of 0.1°.

Citation Wang Z, Dong W. Towards Aerial Collaborative Stereo: Real-Time Cross-Camera Feature Association and Relative Pose Estimation for UAVs[J]. IEEE Sensors Journal, 2025.

Link https://ieeexplore.ieee.org/abstract/document/10856812/

Tracking Control on Closed-Loop-Identification UAV with Constrained Attitude Angle Based on Barrier Lyapunov Function

Keywords

State constrained, Trajectory tracking, Mico UAV, Adaptive control, System identification

Abstract

In this paper, the trajectory tracking problem of the Unmanned Aerial Vehicle (UAV) is considered. Firstly, different from the accurate models adopted in most of existed works, we consider a concise and effective model in which the inertia link delay phenomenon is considered, and an adaptive back stepping controller is designed to handle the model uncertainty. Further-more, considering the fact that the attitude angle of UAV should be limited within a set of range for safety in real flight. To handle this problem, a barrier Lyapunov function (BLF) based adaptive controller is also proposed to achieve the trajectory tracking task while constrains the attitude angles within a set range. Both simulation and experiment results are provided to verify the effectiveness of the proposed methods.

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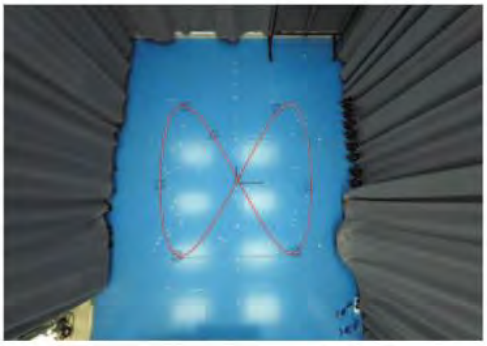
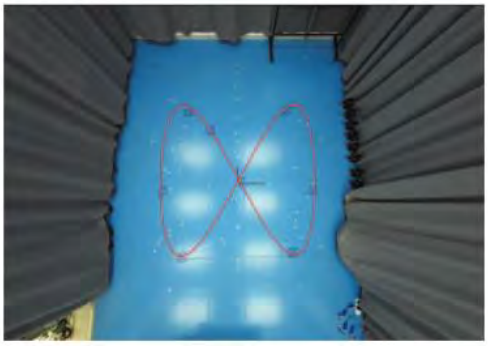


(a) Case II by Controller A



(b) Case II by Controller B

How NOKOV Contributes to the Research

In the conducted experiments, real flight formation tests are executed within an indoor NOKOV setup. The NOKOV motion capture system is instrumental in acquiring marker information, which is processed on a PC to facilitate localization and obstacle detection capabilities. This setup allows forreal-time adjustments to the UAV's thrust and direction, lever-aging precise position data provided by the Motion Capture(MoCap) system, thus enabling the UAV to accurately track the desired trajectory \[15]. In addition, this paper conducts experimental validation using the Crazyflie 2.0.

Citation Wang Z, Wang W, Wang Z, et al. Tracking Control on Closed-Loop-Identification UAV with Constrained Attitude Angle Based on Barrier Lyapunov Function[C]//2024 China Automation Congress (CAC). IEEE, 2024: 5020-5025.

Link https://ieeexplore.ieee.org/abstract/document/10865750

Trajectory Optimization for 3D Shape-Changing Robots with Differential Mobile Base

Keywords

Solid modeling, Three-dimensional displays, Shape, Computational modeling, Manipulators, Planning, Collision avoidance

Abstract

Service robots have attracted extensive attention due to specially designed functions, such as mobile manipulators or robots with extra structures. For robots that have changing shapes, autonomous navigation in the real world presents new challenges. In this paper, we propose a trajectory optimization method for differential-drive mobile robots with controllable changing shapes in dense 3D environments. We model the whole-body trajectory as a polynomial trajectory that satisfies the nonholonomic dynamics of the base and dynamics of the extra joints. These constraints are converted into soft constraints, and an activation function for dense sampling is applied to avoid nonlinear mutations. In addition, we guarantee the safety of full shape by limiting the system's distance from obstacles. To comprehensively simulate a large extent of height and width changes, we designed a novel Shape-Changing Robot with a Differential Base (SCR-DB). Our global trajectory optimization gives a smooth and collision-free trajectory for SCR-DB at a low computational cost. We present vast simulations and real-world experiments to validate our performance, including coupled whole-body and independent differential-driven vehicle motion planning.

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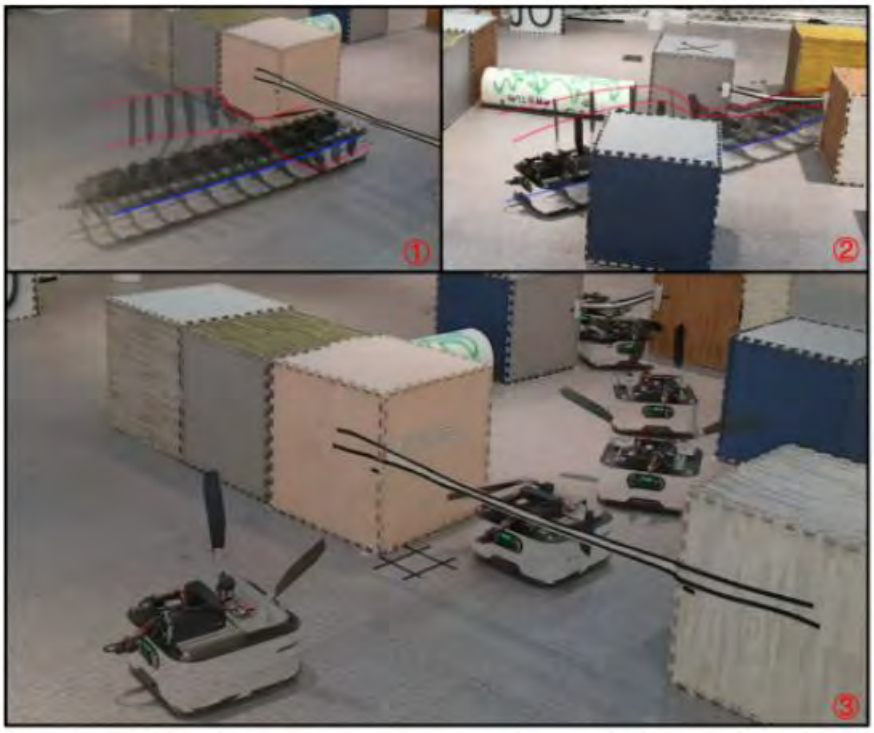

Fig. 8. Real-world experiment.

How NOKOV Contributes to the Research

We use the motion capture system for positioning and map the environment in advance. The robot's movement is shown in Fig. 8, which shows that the robot can avoid obstacles following the planned trajectory.

Citation Zhang M, Xu C, Gao F, et al. Trajectory optimization for 3d shape-changing robots with differential mobile base[C]//2023 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2023: 10104-10110.

Link https://ieeexplore.ieee.org/abstract/document/10160911

Trajectory tracking and load anti-swing control for quadrotor-slung-load system under time-varying disturbances: A dual time-varying uncertainty and disturbance estimator-based approach

Keywords

Quadrotor-slung-load system, Load anti-swing, Trajectory tracking, Time-varying uncertainty and disturbance estimator

Abstract

In aerial transportation and delivery of a slung load by a quadrotor, existing control frameworks with a single, fixed-parameter-based disturbance estimator might not sufficiently consider and address the time-varying disturbances present in both quadrotor trajectory tracking and load anti-swing control loops, particularly during different flight phases. To better reject these disturbances, we propose a dual, time-varying uncertainty and disturbance estimator (TVUDE)-based control framework. In the framework, the fixed parameter of the classic disturbance estimator is replaced by a time-varying parameter. This replacement enables the estimator to better respond to the bandwidth and amplitude change of the disturbance, rather than seeking an "optimal" constant parameter once and for all. Furthermore, two TVUDEs are designed to respectively reject the disturbances in both two control loops such that good overall robustness against multi-loop disturbances is guaranteed. Comparative simulation and experimental results validate the performance superiority of the proposed framework over existing methods.

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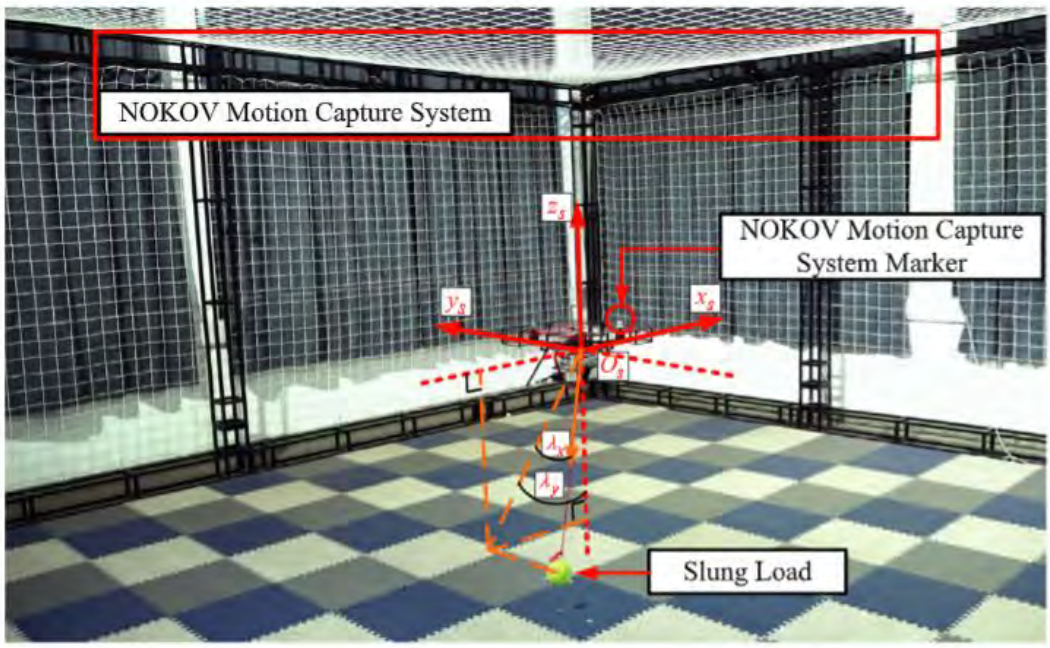

Fig. 11. The experimental scenario.

How NOKOV Contributes to the Research

6.1. Experimental setup
The experiments are conducted in an indoor environment equippedwith a NOKOV Motion Capture (MoCap)System. As shown in Fig.11,twelve MoCap cameras track the reflective markers on both thequadrotor and the load, calculating their positions and linear velocitiesin the local frame. The experiment experimental hardware configuration are as follows: The quadrotor is an Amoy P230 quadrotorequipped with a Pixracer Rl5 flight controller, an AllSpark on-boardcomputer, four KV 1750 motors and 6-inch three-bladed propellers, anda 4S 5300 mAh battery. The proposed and compared controllers areimplemented by using Matlab/Simulink on the ground Positioning andControl Computer. The ground control software communicates withthe on-board computer via Robot Operating System (ROS) messages toexchange the acceleration control commands

Citation Bai H, Qi S, Hu R, et al. Trajectory tracking and load anti-swing control for quadrotor-slung-load system under time-varying disturbances: A dual time-varying uncertainty and disturbance estimator-based approach[J]. Control Engineering Practice, 2025, 165: 106518.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001584107600001

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Ultra-Wideband assisted Visual-Inertial Localization Correction System with Position-Unknown UWB Anchors

Abstract

Given the fact that visual-inertial odometry (VIO) is faced with the challenges of localization drift in the long run, we utilize drift-free Ultra-Wideband (UWB) measurements to eliminate accumulated errors in VIO. Existing UWB-VIO fusion methods are mostly constrained by the accuracy of prior UWB anchor positions. However, in large-scale localization scenarios, the precise locations of UWB anchors are difficult to obtain, and the offline calibration process is complex, significantly limiting flexibility. In this paper, we firstly design a lightweight initialization method based on a dual sliding window structure, which can rapidly obtain initial guesses for the UWB anchor coordinates. After that, we further propose a joint estimation system to refine the anchor coordinates while estimating the correction for VIO. The system combines filter-based and optimization-based methods, which mainly consists of an initialization module and a nonlinear estimator module. The filter in the initialization module provides optimization initial values and covariances, and mutually, the optimization results from the nonlinear estimator provide priors for the filter. Finally, the performance of our proposed approach is verified through both public datasets and real-world experiment. Our project, along with our dataset, has been open-sourced in the form of ROS package and ROS bag.

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Fig. 4. **The experimental setup.** NOKOV motion capture system directly measures the ground truth, anchor coordinates and extrinsic parameters between sensors. The drone is equipped with the necessary processor and sensors.

How NOKOV Contributes to the Research

As shown in Fig. 4, the experimental setup is supported by the NOKOV motion capture system (accuracy ± 0.2mm), which directly provides ground truth, anchor coordinates, external parameters of sensors, and other external information, ensuring the accuracy of the dataset. The quadrotor is equipped with the processor and sensors required for localization, including: 1) Intel D435i depth camera, which can output binocular images with the resolution of 640×480 at 30 Hz. 2) IMU module uses the MPU6000 embedded in the PixHawk v3X flight controller to output at nearly 200 Hz. 3) UWB module are commercially available DWM1000 modules from YCHIOT, whose ranging error is within 5cm after calibration and filtering. 4) The localization algorithm is deployed on an Intel NUC minicomputer with a processor of Intel Core TM i7-1165G7 @ 2.80GHz×8. The drone is controlled to fly a circular trajectory to ensure that the visual loop closure can be triggered, allowing for a comparison between the proposed method and loop closure in drift correction. Sensor data are collected during the drone's actual flight for localization.

Citation Y. Xing, W. Li, F. Pan and X. Feng, "Ultra-Wideband assisted Visual-Inertial Localization Correction System with Position-Unknown UWB Anchors," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 12884-12891, doi: 10.1109/IROS60139.2025.11246170.

Link https://ieeexplore.ieee.org/document/11246170

Universal Trajectory Optimization Framework for Differential Drive Robot Class

Keywords

Motion planning, trajectory optimization, differential drive robot class, nonholonomic dynamics

Abstract

Differential drive robots are widely used in various scenarios thanks to their straightforward principle, from household service robots to disaster response field robots. The nonholonomic dynamics and possible lateral slip of these robots lead to difficulty in getting feasible and high-quality trajectories. Although there are several types of driving mechanisms for real-world applications, they all share a similar driving principle, which involves controlling the relative motion of independently actuated tracks or wheels to achieve both linear and angular movement. Therefore, a comprehensive trajectory optimization to compute trajectories efficiently for various kinds of differential drive robots is highly desirable. In this paper, we propose a universal trajectory optimization framework, enabling the generation of high-quality trajectories within a restricted computational timeframe for these robots. We introduce a novel trajectory representation based on polynomial parameterization of motion states or their integrals, such as angular and linear velocities, which inherently matches the robots' motion to the control principle. The trajectory optimization problem is formulated to minimize computation complexity while prioritizing safety and operational efficiency. We then build a full-stack autonomous planning and control system to demonstrate its feasibility and robustness. We conduct extensive simulations and real-world testing in crowded environments with three kinds of differential drive robots to validate the effectiveness of our approach.Note to Practitioners—The Differential drive robot, known for its simple mechanics and high maneuverability, is widely used in many applications. However, current methods have limitations in practice when high-performance motion is needed. Due to the state representation in Cartesian space, path planning makes it difficult to consider nonholonomic constraints directly. The existing trajectory optimization cannot effectively constrain the angular velocity and it is difficult to model forward and backward motion into a continuous trajectory. This paper provides a novel trajectory representation that inherently utilizes the motion performance of differential drive robots, which ensures its universality for different platforms, and reduces the time required to generate trajectories to ensure real-time

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performance. Based on this, we propose a robust planning and control framework to achieve efficient navigation. We release the source code at https://zju-fast-lab.github.io/DDR-opt/ facilitating expansion and deployment for practitioners. We validate this framework through extensive experiments, demonstrating its capability to navigate challenging environments.

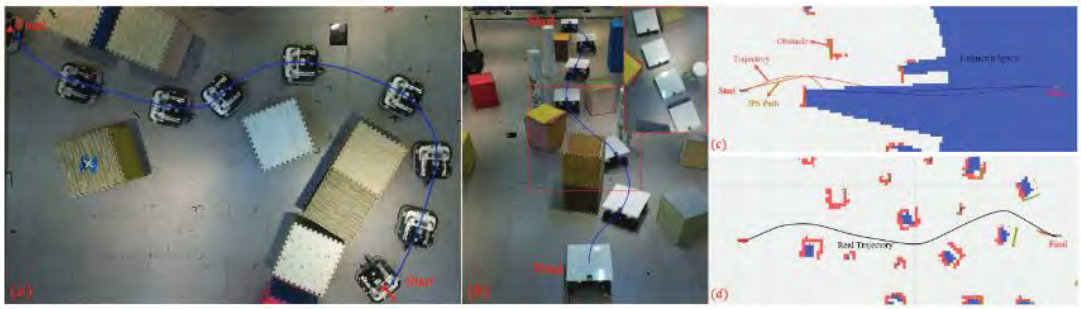

Fig. 14. Planning results. (a)The two-wheeled SDD robot. (b)The four-wheeled SKDD robot. (c)Map and planning result at the starting point of the SKDD robot. (d)Real trajectory of the SKDD robot.

How NOKOV Contributes to the Research

We employ the TRACER MINI2as the two-wheeled SDDrobot platform, which is controlled through linear and angularvelocity. We pre-build the map and utilize the motion capturesystem3for localization. We intentionally task the robot withlarge-angle maneuvers, where there is a significant differencebetween the initial orientation and the upcoming forwarddirection. We constrain the maximum velocity tovmax=1.0m/sand the maximum angular velocity to ω max=1.0rad/s. Theresult is shown in Fig. 14(a), demonstrating the capability of our proposed method to produce smooth motion

Citation Zhang M, Chen N, Wang H, et al. Universal trajectory optimization framework for differential drive robot class[J]. IEEE Transactions on Automation Science and Engineering, 2025.

Link https://ieeexplore.ieee.org/document/10924228

Unlocking aerobatic potential of quadcopters: Autonomous freestyle flight generation and execution

Keywords

TRAJECTORY GENERATION, ROBUST, TRACKING

Abstract

Quadcopter drones are capable of executing complex aerobatic maneuvers when controlled manually by skilled pilots but are limited to simple aerobatic actions when flying autonomously in open spaces. As such, this study introduces a comprehensive system that enables drones to generate and execute sophisticated aerobatic maneuvers in complex environments with dense obstacle distributions. A universal representation is proposed, succinctly capturing flight as a series of discrete aerobatic intentions. These intentions consist of topology and attitude changes, which can be combined in various ways to describe intricate flight maneuvers. A spatial-temporal joint optimization trajectory planner is also introduced to generate dynamically feasible trajectories that are as smooth as possible and devoid of collisions. In addition, we investigate unique yaw sensitivity issues in aerobatic flight and identify the inherent influence of differential flatness singularities on yaw rotations while avoiding associated dynamics issues. A series of ablation studies confirmed the necessity of these spatial-temporal joint optimization and yaw compensation strategies. Additional simulations and physical experiments validated the stability and feasibility of our proposed system for improving uncrewed aerial flight. The proposed system enables drones to autonomously achieve flight performance usually reserved for professional pilots, unlocking boundless potential for aerobatic flight evolution in uncrewed aerial vehicles.

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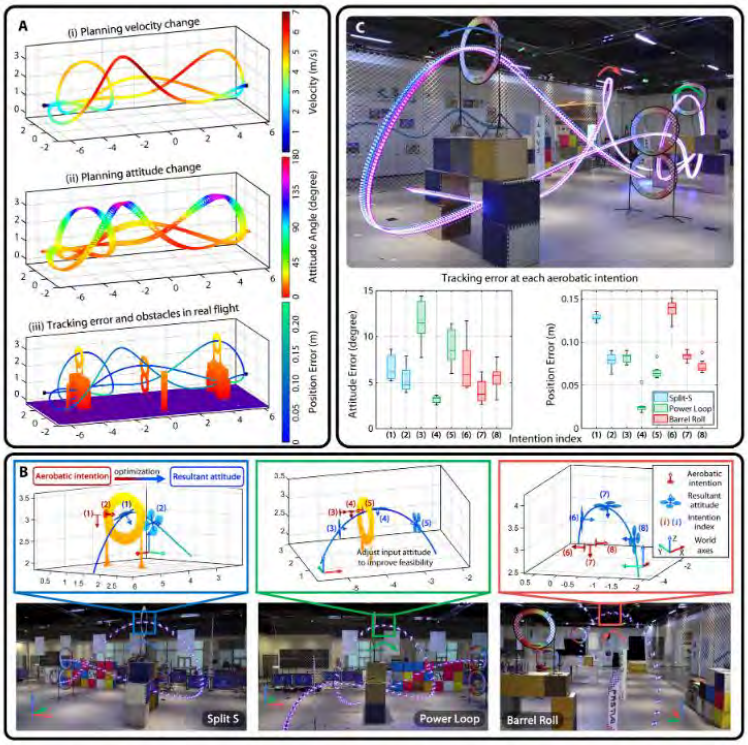

Fig. 4. Performing aerobatics while avoiding obstacles. (**A**) Overview of the aerobatic flight trajectory. (i) The planned trajectory and corresponding speed. (ii) The planned trajectory attitude. The attitude angle was defined as the angle between the direction of the drone's *z* axis and the direction opposite the acceleration of gravity. The attitude of the drone at each sampling point was represented by a circle perpendicular to the *z* axis. (iii) Environmental obstacles and tracking errors for trajectory execution. (**B**) Specific input intentions for each aerobatic maneuver, corresponding position and attitude for the planned trajectory, and snapshots of the actual flight trajectory. The point cloud and trajectory are of the same significance as [(A), iii]. (**C**) Real aerobatic snapshots and statistics. The quadrotor was equipped with light bars on all four arms, with the nose bar colored purple and the tail colored blue. The horizontal coordinates in the box plot represent the indices of the eight aerobatic intentions entered by the user. All data were derived from the eight complete aerobatic flights.

How NOKOV Contributes to the Research

The experiments discussed previously highlighted the impressive performance achieved by the proposed system in large- scale aero-batic flight scenarios. In comparison, the experiment shown in Fig. 4 was intended to evaluate system capabilities for generating aerobatic trajectories in confined spaces, which require drones to perform ma-neuvers near obstacles. As illustrated in Fig. 4C, the experiment re-stricted aerobatic flight to within the narrow range of a motion capture system at a height of only 3.5 m. Tunnels, circular gates, and flags were strategically positioned in the environment and served as obstacles. Aerobatic intentions were incorporated into the system, which generated agile aerobatic trajectories designed to avoid obsta-cles. This included shuttling through circular gates in reverse and fre-quent passage through tunnels (see Fig. 4B and movie S3).

Citation Mingyang Wang et al. ,Unlocking aerobatic potential of quadcopters: Autonomous freestyle flight generation and execution.Sci. Robot.10,eadp9905(2025).DOI:10.1126/scirobotics.adp9905

Link https://www.science.org/doi/10.1126/scirobotics.adp9905

Versatile Tasks on Integrated Aerial Platforms Using Only Onboard Sensors: Control, Estimation, and Validation

Keywords

Integrated aerial platform (IAP), interaction task, loose fusion, perception-aware control, visual-inertial localization

Abstract

Connecting multiple aerial vehicles to a rigid central platform through passive spherical joints holds the potential to construct a fully actuated aerial platform. The integration of multiple vehicles enhances efficiency in tasks like mapping and object reconnaissance. This article proposes a control and state estimation framework for the integrated aerial platform (IAP), enabling it to perform versatile tasks like object reconnaissance and physical interactive tasks with only onboard sensors. In the framework, the 6-D motion control serves as the low-level controller, while the high-level controller comprises a 6-D admittance filter and a perception-aware attitude correction module. The 6-D admittance filter, serving as the interaction controller, is adaptable for aerial interaction tasks. The perception-aware attitude correction algorithm is carefully designed by adopting a geometric model predictive controller (MPC). This algorithm, incorporating both offline and online calculations, proves to be well-suited for the intricate dynamics of an IAP. A 6-D direct wrench controller is also developed for the IAP. Notably, both the interaction controller and the direct wrench controller operate without reliance on force/torque sensors. Instead, a wrench observer algorithm is devised, considering external disturbances. In addition, based on the kinematics constraints of the multiple aerials in the platform, a fusion algorithm for multiple visual-inertial odometry and kinematics constraints is developed, providing more accurate localization. A prototype of the IAP is constructed, and its capabilities are demonstrated through experiments including perception-aware object reconnaissance, aerial mapping, aerial peg-in-hole task, and 6-D contact wrench generation. All experiments are conducted exclusively with onboard sensors. These tasks exemplify the merits of the proposed IAP and validate the effectiveness of the proposed control framework and fusion algorithm.

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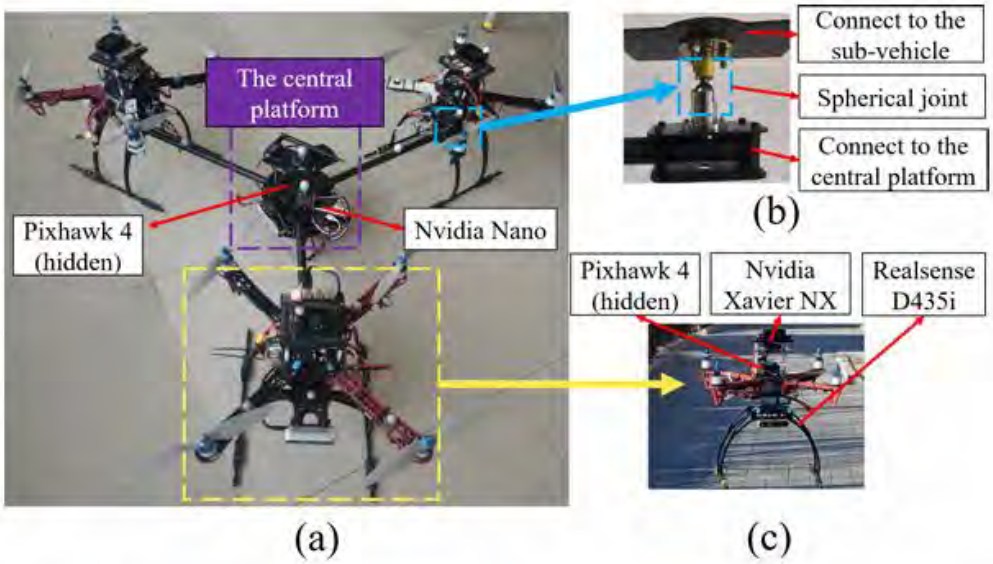

Fig. 13. Experimental platform. (a) Three-agent IAP prototype. (b) Spherical joint and the interconnection mechanism. (c) Subvehicle, which can conduct an independent flight.

How NOKOV Contributes to the Research

Collaborative Localization:We validate the RTE methodin our collected dataset (V_01-03) and a simulation dataset(C_04-05). The real-life dataset is collected offlined with ourIAP prototype shown in Fig.13, which contains diverse tra-jectories. The ground truth is provided by the motion capturesystem NOKOV.2The simulation dataset is generated by ourhigh-photo-fidelity simulator\[65], which includes the stereocamera data (20 Hz) and the IMU data (200 Hz). Two simplecircle trajectories with fast speed are considered to validate the performance of our method in less diverse trajectories.

Citation Wang K, Lai G, Yu Y, et al. Versatile Tasks on Integrated Aerial Platforms Using Only Onboard Sensors: Control, Estimation, and Validation[J]. IEEE Transactions on Robotics, 2025.

Link https://ieeexplore.ieee.org/document/10994382

VISC: mmWave Radar Scene Flow Estimation using Pervasive Visual-Inertial Supervision

Abstract

This work proposes a mmWave radar's scene flow estimation framework supervised by data from a widespread visual-inertial (VI) sensor suite, allowing crowdsourced training data from smart vehicles. Current scene flow estimation methods for mmWave radar are typically supervised by dense point clouds from 3D LiDARs, which are expensive and not widely available in smart vehicles. While VI data are more accessible, visual images alone cannot capture the 3D motions of moving objects, making it difficult to supervise their scene flow. Moreover, the temporal drift of VI rigid transformation also degenerates the scene flow estimation of static points. To address these challenges, we propose a drift-free rigid transformation estimator that fuses kinematic model-based ego-motions with neural network-learned results. It provides strong supervision signals to radar-based rigid transformation and infers the scene flow of static points. Then, we develop an optical-mmWave supervision extraction module that extracts the supervision signals of radar rigid transformation and scene flow. It strengthens the supervision by learning the scene flow of dynamic points with the joint constraints of optical and mmWave radar measurements. Extensive experiments demonstrate that, in smoke-filled environments, our mmWave radar performs state-of-the-art (SOTA) approaches us.

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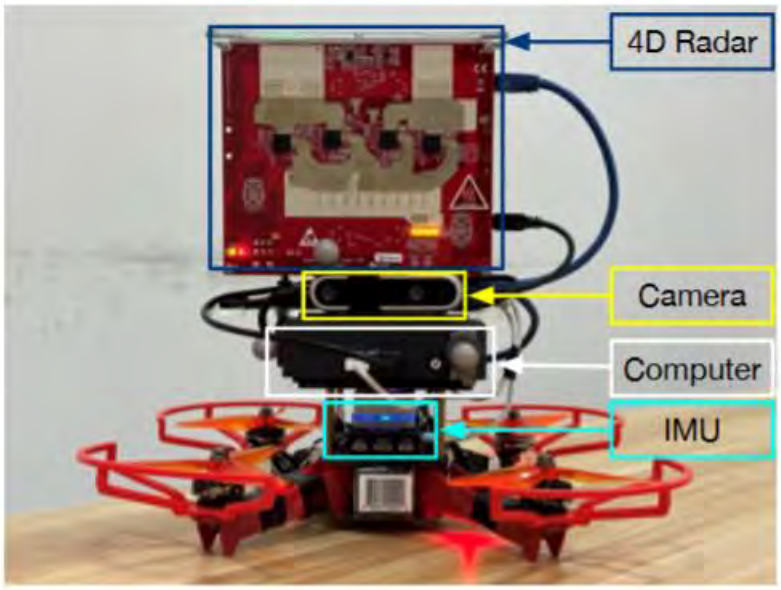

Fig. 3. The key components of our customized platform include a 4D radar, an RGB camera, an IMU, and a mini-computer.

How NOKOV Contributes to the Research

Ground truth labelling.Although VISC does not need the ground truth labels to train the model, we still need it to evaluate the performance. Following \[8], we annotate the ground truth scene flow by object detections,i.e., bounding boxes, and ground truth radar rigid transformation. In the indoor scene, we use NOKOV motion capture system to obtain the ground truth rigid transformation. In the outdoor scene, we take VINS-Fusion to fuse images, IMU and GPS measurements to obtain the ground truth rigid transformation

Citation K. Liu et al., "VISC: mmWave Radar Scene Flow Estimation using Pervasive Visual-Inertial Supervision," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 6765-6770, doi: 10.1109/IROS60139.2025.11246830.

Link https://ieeexplore.ieee.org/document/11246830

Zonotopic Attack Detection and Control Algorithm for Vehicle Platooning

Keywords

Zonotopic attack detection, model predictive control, vehicle platooning, stealthy attack

Abstract

This paper focuses on enhancing the detection of cyber attacks and implementing distributed control mechanisms in automated vehicles, specifically to ensure lateral stability and reliable vehicle following. To accomplish the objective, the paper presents a comprehensive architecture that consists of an attack detector, a resilient observer, and a distributed model predictive controller. The zonotopic attack detector can identify attacks launched against sensor measurements. The observer guarantees tight error bounds, despite the presence of stealthy attacks. The stability of the entire system is ensured by the proposed model predictive controller. The numerical simulations and physical experiments demonstrate that even in the presence of stealthy attacks, the vehicle state estimation errors remain bounded and formation stability is maintained.

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Fig. 2. Turtlebot3 robot

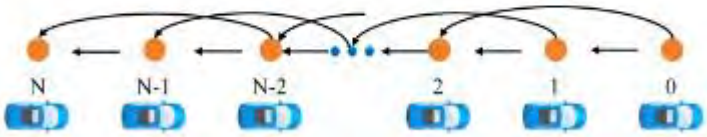

Fig. 3. Two-predecessor following (TPF) communication topology

How NOKOV Contributes to the Research

To verify the effectiveness of the proposed algorithm, nu-merical simulations and physical experiments in a laboratoryenvironment are conducted. The vehicle attack detection andcontrol algorithm is simulated in MATLAB R2019b, and ex-perimental verification is performed using TurtleBot3 robots,as shown in Fig. 2. During the experiment, the NOKOV motion capture system was used to obtain the vehicles' positionand velocity information. In both the numerical simulationsand experimental verification, the TPF communication topol-ogy is adopted, as shown in Fig. 3.

Citation Sun N, Wang W, Wu H, et al. Zonotopic Attack Detection and Control Algorithm for Vehicle Platooning[J]. IEEE Transactions on Vehicular Technology, 2025.

Link https://ieeexplore.ieee.org/document/1096407

FlyAware: Inertia-Aware Aerial via Vision-Based Estimation and Post-Grasp Adaptation

Keywords

Aerial systems: perception and autonomy, robust/adaptive control, calibration and identification.

Abstract

Aerial manipulators (AMs) are gaining increasing attention in automated transportation and emergency services due to their superior dexterity compared to conventional multirotor drones. However, their practical deployment is challenged by the complexity of time-varying inertial parameters, which are highly sensitive to payload variations and manipulator configurations. Inspired by human strategies for interacting with unknown objects, this letter presents a novel onboard framework for robust aerial manipulation. The proposed system integrates a vision-based pre-grasp inertia estimation module with a post-grasp adaptation mechanism, enabling real-time estimation and adaptation of inertial dynamics. For control, we develop an inertia-aware adaptive control strategy based on gain scheduling, and assess its robustness via frequency-domain system identification. Our study provides new insights into post-grasp control for AMs, and real-world experiments validate the effectiveness and feasibility of the proposed framework.

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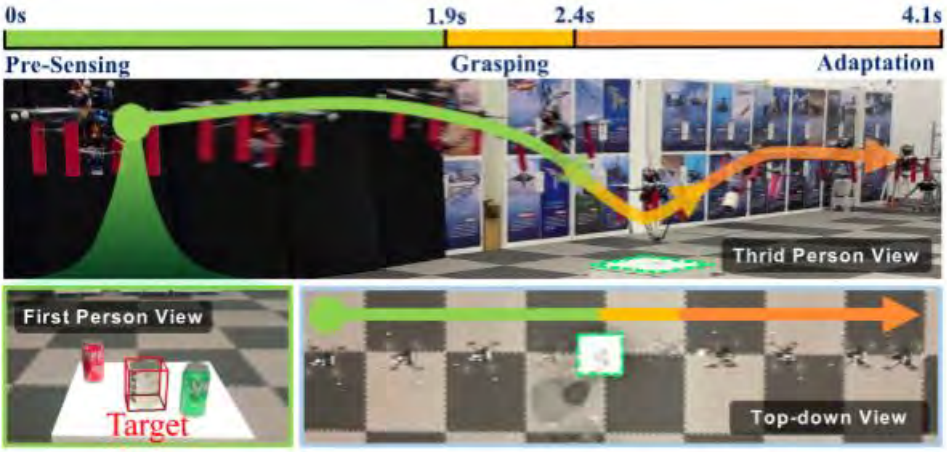

Fig. 1. Real-world experiment: The aerial manipulator pre-senses and grasps objects arbitrarily placed on a table by a human operator.

How NOKOV Contributes to the Research

V. EXPERIMENTS AND RESULTS
We evaluate our methods on a custom AM platform weighing 1.379 kg and measuring 240×240×220 mm3. The platform is equipped with a NxtPX4v2 flight controller, an Intel RealSense D435i depth camera, and an NVIDIA Jetson Orin NX 16 GB for onboard computation. The delta arm is actuated by three DYNAMIXEL XL430-W250-T servo motors and equipped with an end-effector consisting of three suction cups driven by a vacuum pump. Fig. 2 provides an overview of the platform. Our system is developed in C++11 on Ubuntu 20.04 ROS Noetic with parameters listed in Table I, where L1 Quad \[33] is applied only to rotational dynamics. Accurate positioning is provided by the**NOKOV motion capture***system****, while perception, planning, and control modules are executed on the onboard computer.*

Citation B. Ye et al., "FlyAware: Inertia-Aware Aerial Manipulation via Vision-Based Estimation and Post-Grasp Adaptation," in IEEE Robotics and Automation Letters, vol. 11, no. 3, pp. 3780-3787, March 2026, doi: 10.1109/LRA.2026.3662562.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001694547300004

SA-MPPI: Sensitivity-Aware Model Predictive Path Integral Control for Robust and Agile Quadrotor Flight

Abstract

Reliable quadrotor control in dynamic environments remains challenging due to external disturbances and internal uncertainties. While Model Predictive Path Integral (MPPI) control enables agile maneuvers through sampling-based optimization, its performance often degrades under such unmodeled uncertainties, leading to brittle and unsafe behavior. To address this, we propose SA-MPPI, a novel robust MPC framework that integrates asynchronous guidance with a novel open-loop sensitivity metric. The asynchronous module leverages a slower auxiliary controller to generate an informed sampling distribution, improving convergence without introducing latency. The sensitivity metric penalizes high-variance trajectories under sampled disturbances via nested Monte Carlo rollouts, embedding robustness directly into the optimization. Extensive simulations and real-world quadrotor experiments demonstrate that SA-MPPI outperforms adaptive baselines, reducing tracking errors by up to 47% under significant wind disturbances while achieving over 2× higher computational efficiency. These results highlight SA-MPPI's ability to deliver low-latency, safe, and predictable control in uncertain, dynamic environments.

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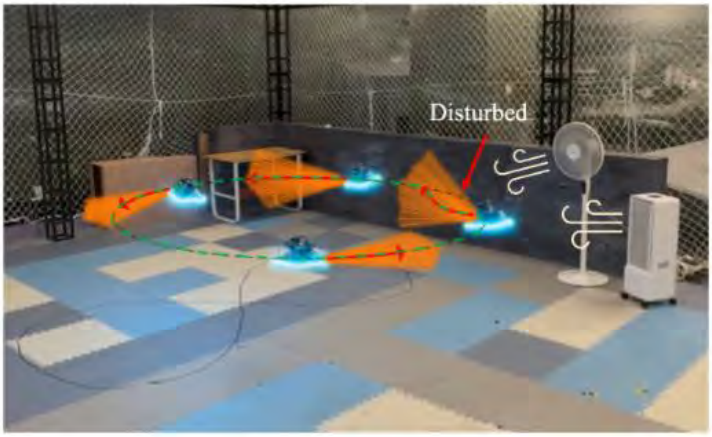

Fig. 1: Trajectory of a real-world flight experiment. The proposed SA-MPPI controller enables accurate circular trajectory tracking under significant wind disturbance from a fan, demonstrating robust and precise control in challenging environments.

How NOKOV Contributes to the Research

The resulting commands are sent to a PX4-based low-level controller via Micro Air Vehicle link (MAVLink), with state estimation provided by a 200 Hz**Nokov motion capture system****. A 30 Hz low-pass filter is applied to angular velocity commands to reduce sampling-induced chatter. **

Citation 暂无

Link 暂无

A Novel Multi-Strategy Hybrid Gray Wolf Optimization for Multi-UAV Cooperative Path Planning OA

Keywords

unmanned aerial vehicle (UAV); cooperative path planning; gray wolf optimization

Abstract

In recent years, unmanned aerial vehicles (UAVs) cooperative path planning is attracting more and more research attention. For the multi-UAV cooperative path planning problem, the path planning problem in three-dimensional (3D) environment is transformed into an optimization problem by introducing the fitness function and constraints such as minimizing path length, maintaining a low and stable flight altitude, and avoiding threat zones. A multi-strategy hybrid grey wolf optimization (MSHGWO) algorithm is proposed to address this problem. Firstly, a chaotic Cubic mapping is introduced to initialize the grey wolf positions to make its initial position distribution more uniform. Secondly, an adaptive adjustment weight factor is designed, which can adjust the movement weight based on the rate of fitness value decrease within a unit Euclidean distance, thereby improving the quality of the population. Finally, an elite opposition-based learning strategy is introduced to improve the population diversity so that the population jumps out of the local optimum. Simulation results indicate that the MSHGWO is capable of generating constraint-compliant paths for each UAV in complex 3D environments. Furthermore, the MSHGWO outperforms other algorithms in terms of convergence speed and solution quality. Meanwhile, flight experiments were conducted to validate the path planning capability of MSHGWO in real-world obstacle environments, further demonstrating the feasibility of the proposed multi-UAV cooperative path planning approach.

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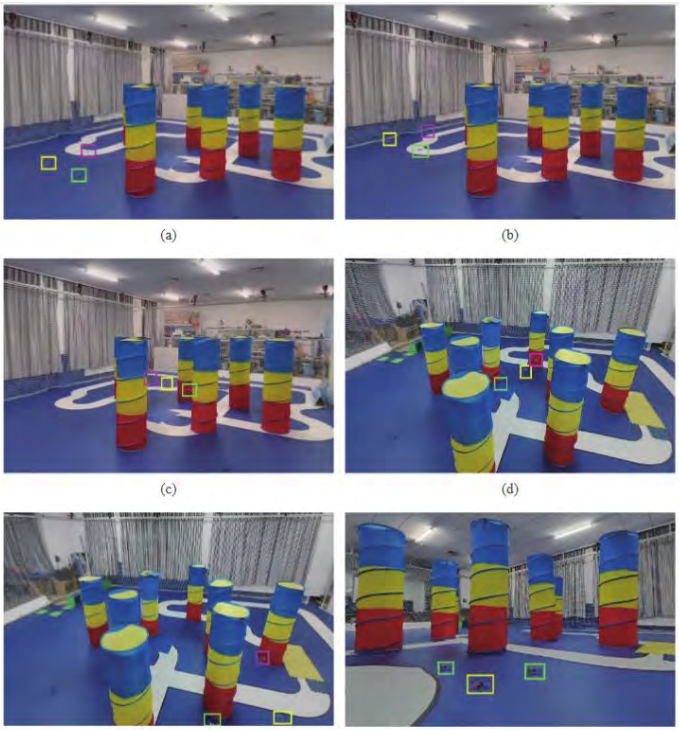

Fig. 20 Examples of physical flight tests: (a) initial positions of UAVs; (b) UAVs that take off from the ground; (c) UAVs after passing the first row of obstacles; (d) UAVs after traversing the second row of obstacles; (e) UAV 2 that approaches its target while UAV 1 and UAV 3 navigate the final obstacle row; (f) final positions of UAVs after successfully reaching their target points

How NOKOV Contributes to the Research

4.4 Real-World Experiment
*To further validate the effectiveness of the MSHGWO algorithm for path planning in the real world, flight experiments were conducted with three UAVs in an indoor environment. Fig. 18 illustrates the UAV swarm flight platform, which includes the **NOKOV motion capture system**, the robot operating system, a wireless local area network, a pair of UAV communication modules and a set of quadcopters. The motion capture (MoCap) system consists of sixteen motion capture cameras, an ethernet switch and data processing software.*

Citation Xiong H, Liu X, Dai T, et al. A Novel Multi-Strategy Hybrid Gray Wolf Optimization for Multi-UAV Cooperative Path Planning[J]. Journal of Beijing Institute of Technology, 2026, 35(1): 1.

Link

https://kns.cnki.net/kcms2/article/abstract?v=H8HwaL3t0AuUQ1xk3vylBn1T7j1fskvZgJBv7Say7uqDC9ijRH5WpSygmyKfq7_isuy_iNjZswuBo1GGBJBnlUOZY-J_KyFX3Ly5yXkrBJpjyoljrTQ1bUY1dko7-Vq3y23Ax_53hJ_8z7q5aj2wkRk-uFGMbRnFD095vlOR6kyZXvQ7gKz2ow==&uniplatform=NZKPT&language=CHS

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A Visual Target Navigation Method for Quadrotor Based on Large Language Model in Unknown Environment

Abstract

This paper proposes a novel Large Language Model (LLM)-based visual target navigation framework for quadrotors in unknown environments. Leveraging the semantic knowledge of LLMs, our method enables autonomous exploration based on natural language instructions. We design an intelligent planner using specialized prompt templates that operates in two phases: first, deriving global search sequences via probabilistic inference; second, dynamically generating sub-goal waypoints by fusing visual observations with statistical priors and LLM-derived scene relevance metrics. The quadrotor then executes a progressive search via path planning algorithms. Simulation results indicate that our fused method outperforms single-modality baselines by approximately 20%. Furthermore, physical flight experiments demonstrate success rates of 56% in Cross-layout and 48% in T-shaped layout scenarios. These results, while reflecting the inherent challenges of perceptual occlusion and planning uncertainty, validate the feasibility and potential of the proposed framework in real-world applications.

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Figure 6. The physical experimental environment setups. (**Left**) The Cross layout configuration, featuring four distinct functional zones (Kitchen, Office, etc.) separated by partition walls. (**Right**) The T-shaped layout configuration. The scenes are populated with common household objects serving as navigation targets. Virtual background images are pasted on the walls to enhance semantic richness for visual recognition.

How NOKOV Contributes to the Research

In the real experiments, the Nokov system was used to achieve the positioning of the quadrotor. Due to the use of a motion capture system for positioning, the flight experiment area must remain within the camera's field of view. Consequently, various indoor scenarios were constructed within the motion capture system's experimental area. Indoor environments often contain numerous objects, some of which are difficult to incorporate due to their complexity. To address this, virtual background images were used as substitutes, enhancing the richness of the physical experiment scenarios and providing additional contextual information. For this study, four indoor scenarios were created, representing a kitchen, a reading room, an office, and a bathroom. Small physical objects and virtual background images were used to construct these environments, with walls (1.8 m high and 0.6 m thick) installed to separate the scenes. Two layouts were designed for the physical experiments, as shown in Figure 6, arranging the four rooms in a cross layout and a T-shaped layout, while maintaining consistent interior arrangements across all rooms.

Citation Liu Y, Ma Z, Guo J, et al. A Visual Target Navigation Method for Quadrotor Based on Large Language Model in Unknown Environment[J]. Drones, 2026, 10(2): 134.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001701527100001

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Active adaption compensation control of mechanically-docked vehicles against composite motion interferences

Keywords

Mechanically-docked vehicles; Cascaded control; Adaptive safety geofencing; Adaptive gain filtering extended state observer; Active fault-tolerant compensation; Motion capture

Abstract

This paper concerns the universal and adaptive control solutions for a class of mechanically docked vehicles under complex motion interference. The kinematic and dynamic models of the connected vehicles are first established, followed by the design of a model-based cascaded control framework. An improved adaptive safety geofencing method is then introduced, integrating capability constraints and barrier functions to modify the reference trajectory within the kinematic loop and ensure position safety near obstacles. Furthermore, an adaptive gain filtering extended state observer (AGFESO) is proposed to achieve low-peak, small-oscillation disturbance estimation from noisy measurements, thereby enhancing the practical robustness of dynamic feedback control through feedforward compensation. In addition, an active fault-tolerant mechanism is developed to optimize the allocation of control inputs at the actuator level, mitigating performance degradation under random actuator faults. Finally, the advantages and effectiveness of the proposed design scheme for connected vehicles under composite interferences are demonstrated by simulation and experimental examples.

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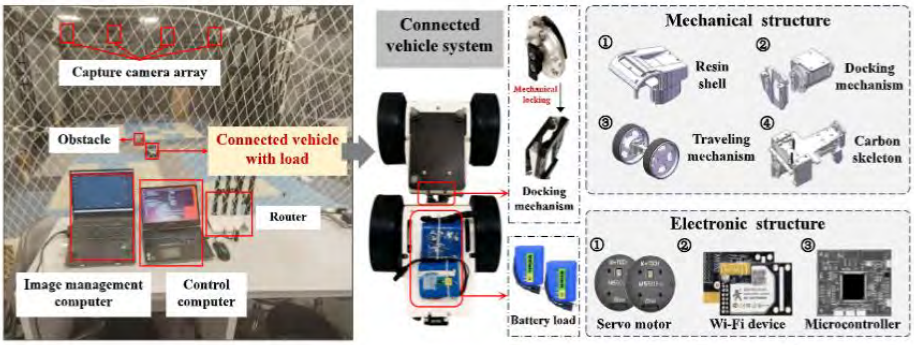

Fig. 4. Experiment verification platform and connected vehicle system.

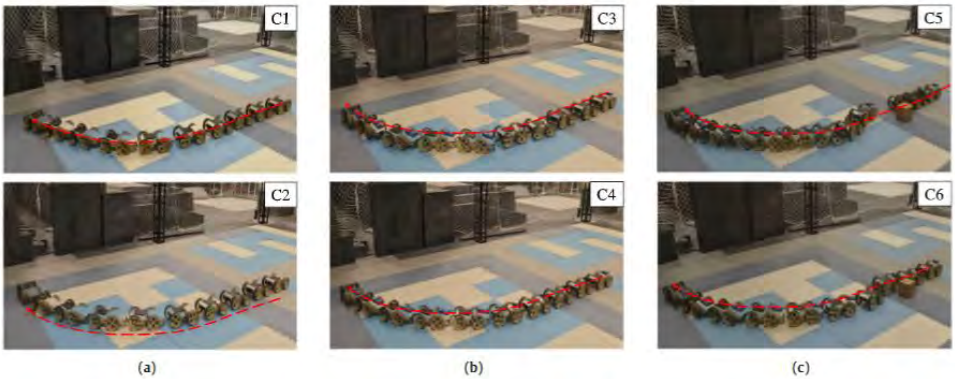

Fig. 5. Experimental image comparison of each moment. (a)–(c): The fault tolerance comparison, robustness comparison and safety smoothness comparison.

How NOKOV Contributes to the Research

The experimental robot consists of two modular units, where the dynamic control, comprising wheel motors and microcontroller, implements the velocity control. An array of motion capture cameras (NOKOV Motion Capture System) and an image computer in the test field are employed to recognize the markers attached to the motion units and obstacles, and to calculate their positions and attitudes in the inertial frame. The kinematic control computer receives the state topics published by the image computer to construct the kinematic controller. Through a local communication network composed of routers, WiFi devices, and the vehicle itself, the controller issues velocity commands and receives the motion states of each unit in real time.

Citation Su X, Wang J, Jiang T, et al. Active adaption compensation control of mechanically-docked vehicles against composite motion interferences[J]. Automatica, 2026, 188: 112948.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001733456200001

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CBAM-ST-GCN: An enhanced DRL-based end-to-end visual navigation framework for mobile robot

Keywords

Mobile robots; Visual navigation; Obstacle avoidance; Deep reinforcement learning; Dynamic environments

Abstract

Visual-based navigation for mobile robot poses significant challenges due to limited visual perception and the presence of unforeseen dynamic obstacles. Deep reinforcement learning (DRL) provides an end-to-end solution by directly mapping raw sensor data to control commands, offering high adaptability and reduced reliance on handcrafted rules. However, high-dimensional visual inputs and the non-stationarity introduced by dynamic obstacles easily make the policy learning of DRL difficult to convergent and unstable. In this paper, an enhanced end-to-end visual navigation framework is proposed for mobile robot operating in dynamic environments, denoted as CBAM-ST-GCN. A convolutional block attention module (CBAM) is introduced into the framework to enhance visual perception by assigning attention weights across spatial and temporal dimensions. Furthermore, a spatio-temporal graph convolutional network (ST-GCN) is designed to capture the behavior features of moving obstacles. In addition, a velocity obstacle (VO) method-based penalty term is incorporated into the reward function for the enhancement of collision avoidance. Extensive simulation results demonstrate that the proposed method achieves superior success rates and significantly higher convergence speed. Real-world experiments further validate the effectiveness and adaptability of the proposed approach in practical scenarios.

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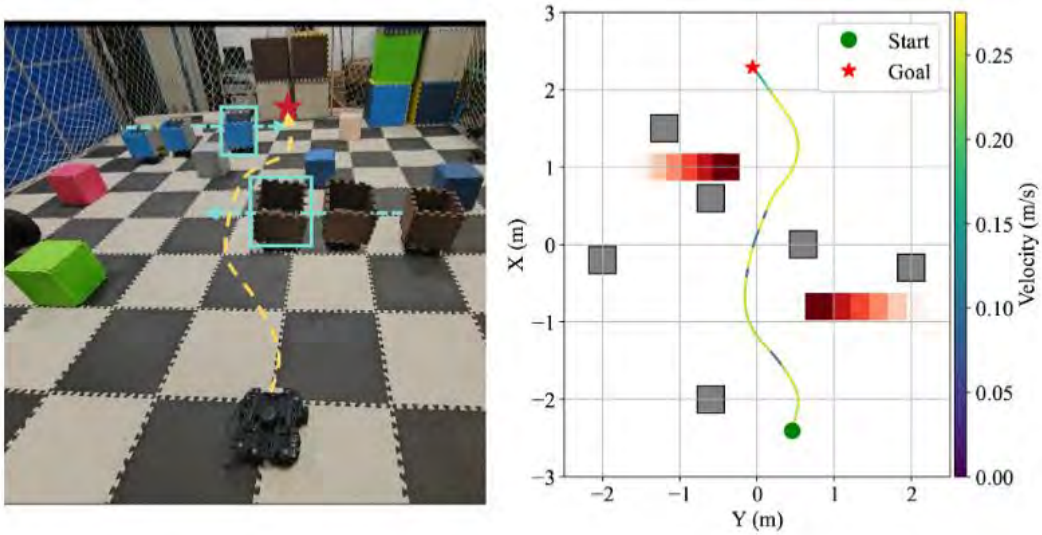

(a) Real-world scene diagram **(b)** Trajectories in the real-world

Fig. 11. Real-world experimental results in Scenario 1.

How NOKOV Contributes to the Research

The experimental platform was based on a Turtlebot3 mobile robot, equipped with a Raspberry Pi 4B onboard computer and a D435i depth camera. The position and velocity of robot were obtained from its onboard IMU sensor, with linear velocity and angular velocity range of (-0.26, 0.26) m/s and (-1, 1) rad/s, respectively. The NOKOV optical motion capture system was applied to acquire the position and heading angle of dynamic obstacles. During autonomous navigation, the ground station received both the mobile robot and the dynamic obstacle information, and then computed the velocity control commands using the proposed algorithm and transmitted them to the TurtleBot3 platform. The ground station was equipped with an NVIDIA 4050 GPU and an i7-12650H CPU. Communication among the mobile robot, the ground station, and the motion capture system was implemented using ROS.

Citation Xie M, Yu W, Jin H, et al. CBAM-ST-GCN: An Enhanced DRL-Based End-to-End Visual Navigation Framework for Mobile Robot[J]. Neural Networks, 2026: 108622.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001676510600001

Formation Control of UAVs Based on Dynamic Vector Velocity Obstacle Method

Keywords

dynamic avoidance plane; dynamic vector velocity obstacle method; fuzzy control; multi-UAV formation; obstacle avoidance; three-dimensional dynamic space; virtual spring algorithm

Abstract

This paper proposes a multiple unmanned aerial vehicle (multi-UAV) formation obstacle avoidance strategy based on the dynamic vector velocity obstacle (DVVO) method, aiming to address the design challenges of the VO method in three-dimensional (3D) dynamic space applications. By considering the relative position and velocity between the UAV and obstacle, a dynamic avoidance plane (DA-Plane) is constructed, which can accurately reflect the collision risk of UAVs in 3D space. On this basis, a dynamic vector velocity obstacle space is designed, and the optimal constant critical escape velocity is selected outside this space to accomplish the obstacle avoidance task, thereby ensuring the smoothness of the flight process. Subsequently, this paper extends the DVVO method to multi-UAV formation based on fuzzy control and the virtual spring algorithm, and designs a differentiated obstacle avoidance strategy to ensure the safe operation of multi-UAV formation in dynamic environments. Simulation and real-world experiments demonstrate that the proposed method enables multi-UAV formation to effectively avoid dynamic obstacles in 3D space and reach the target in a desired formation shape. Compared to the citation algorithm, the DVVO method shows superior performance in terms of smooth motion and computational efficiency. This study effectively simplifies the complex obstacle avoidance problems of multi-UAV formation in 3D dynamic environments, demonstrating significant potential for applications.

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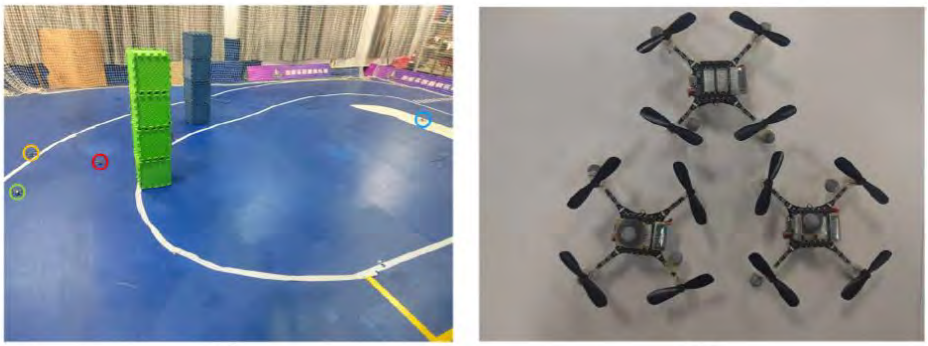

(a) (b)

FIGURE 19 | Experimental environment and subject. (a) Experimental site. (b) Experimental subject. [Color figure can be viewed at wileyonlinelibrary.com]

How NOKOV Contributes to the Research

The experimental platform, similar to that described in (Xiong et al. 2025), consists of the NOKOV Motion Capture System, the robot operating system (ROS), a Wireless Local Area Network (WLAN), a pair of UAV communication modules and four Crazyflie 2.1 micro quadrotors. Among these, three UAVs are utilized to validate the proposed algorithm (see Figure 19b), while the remaining one is employed to simulate a dynamic obstacle (see Figure 19a). The motion capture system is composed of 16 infrared cameras, an ethernet switch, and specialized data processing software. The cameras are uniformly arranged above the experimental area and provide real-time tracking of UAVs and obstacles positions and orientations by detecting reflective markers mounted on them. The relevant parameters of the experiment are detailed in Table 5.

Citation Chen Y, Wei S, Li B, et al. Formation Control of UAVs Based on Dynamic Vector Velocity Obstacle Method[J]. Journal of Field Robotics, 2026.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001672319900001

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MSAF-net: robust measurement acoustic denoising with multi-scale dilated convolutions and dual attention for drone localization

Keywords

measurement acoustic processing; machine learning; robust acoustic signal measurement; fractional discrete wavelet transform; time difference of arrival

Abstract

Drone acoustic source localization is widely employed in fields such as military reconnaissance. However, its positioning pulse signals are vulnerable to strong non-stationary noise generated by the drone's own rotors, resulting in a sharp decline in localization accuracy. Existing deep learning denoising models struggle to balance performance and computational efficiency: complex models incur high computational costs and are unsuitable for the small-sample setting of drone acoustic source localization, while lightweight models suffer from incomplete denoising and introduce 'glitch noise' due to limited receptive fields. To address these issues, this paper proposes a lightweight denoising network called MSAF-net. Its core components are as follows: a multi-scale dilated convolutional residual module which can expand the receptive field of the model; a channel-temporal dual attention mechanism which can enhance waveform detail recovery capability; a fractional-order discrete wavelet transform smoothing algorithm which can suppress the 'glitch noise' introduced by the model. Experiments show that under 5-20 dB noise conditions, MSAF-net outperforms baseline models across SI-signal-to-noise ratio, SDR, and MSE-dB metrics, with only 84 K parameters and 1.8 M FLOPs. In an end-to-end PC-based localization system integrating the proposed network, dynamic localization tracking (Continuously track 67 positioning points) is realized for drones in the near field (<100 m), and the hovering localization error is reduced to 0.1617 m. While maintaining a lightweight profile, MSAF-net significantly improves localization accuracy and system robustness under strong noise, providing a reference solution for embedded real-time acoustic processing.

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How NOKOV Contributes to the Research

The NOKOV optical 3D motion capture system was used as the benchmark for measuring positioning accuracy. In the fixed-point hovering positioning experiment, the 3D position coordinates of 4 UAV fixed-point hover positions were collected, and a comparison was made with the positioning accuracy of the actual deployment of 4 classic neural network denoising models (U-net, LSTM, GAN, DNN). The experimental results and the comparison of positioning errors are shown in figure 13 and table 5. The experimental localization scenario corresponds to a near-field model (<100 m).

Citation Pan Q, Li F, Lu X, et al. MSAF-net: robust measurement acoustic denoising with multi-scale dilated convolutions and dual attention for drone localization[J]. Measurement Science and Technology, 2026, 37(12): 125105.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001729323200001

Nested interaction network enhances responsiveness in collective behavior

Abstract

Survival in dynamic and complex environments requires groups to exhibit a high level of responsiveness to rapidly changing circumstances. Recent studies have shown the role of selective social interactions in driving responsive collective behavior at the individual-level decision making. However, much less effort has been devoted to understanding how structures of interaction networks shape collective responses. Here we show that the highly nested structures enhance responsiveness in schooling fish and swarm robotics. First, analysis of trajectories from schooling Hemigrammus rhodostomus reveals that the high nestedness, quantified through the nestedness metric based on overlap and decreasing fill (NODF), emerges as a key interaction structure feature in maneuverable movements. Using a general contagion model, we then show that the perfectly nested interaction network (PNIN) achieves the optimal information transfer efficiency. Furthermore, we integrate the PNIN into the self-propelled system and demonstrate the advantages of PNIN in facilitating efficient and robust collective responses through semi-physical simulations and 50 real robots. Our study provides a modeling perspective to elucidate collective responses through structural arrangements of interaction networks.

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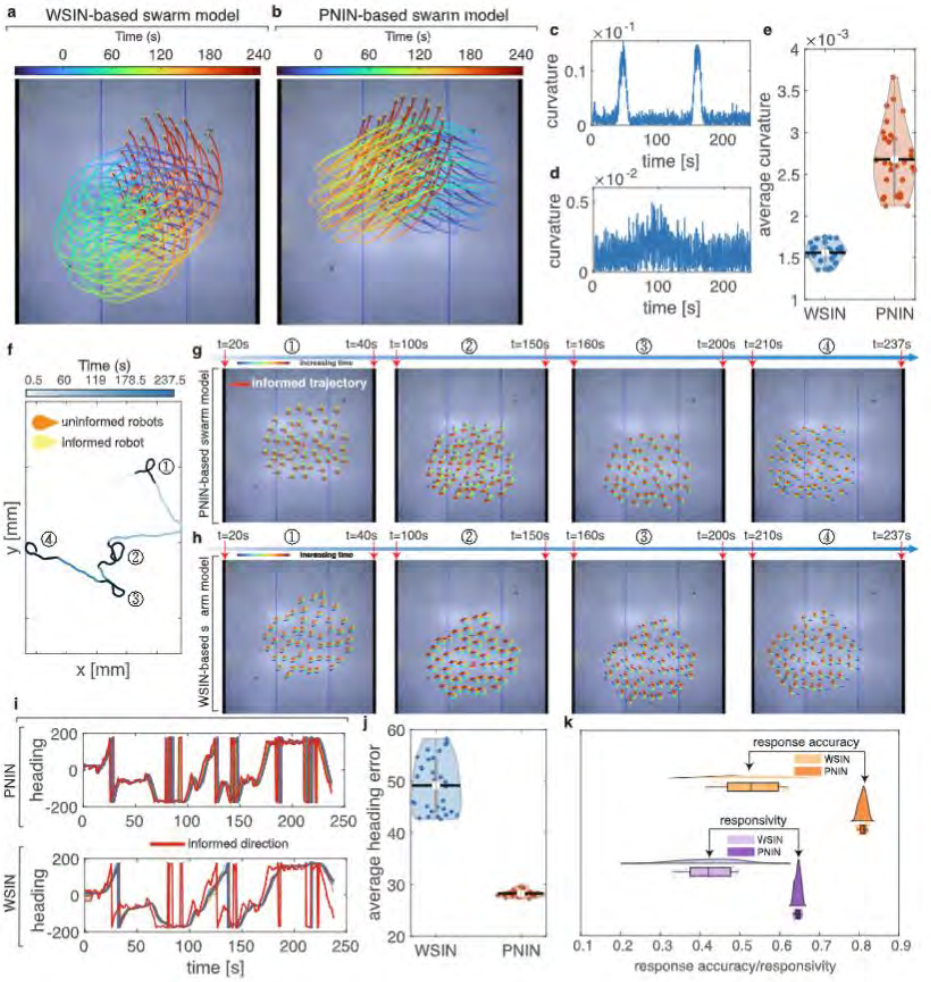

How NOKOV Contributes to the Research

To show the feasibility of the PNIN-based swarm model, we build a swarm robotics validation system within a 6m × 6m experimental arena, referred to as the SwarmBang system(^{16,17}) (see Supplementary Note 11 and Supplementary Fig. 2 for the architecture of the SwarmBang system). The SwarmBang system comprises a motion capture system (NOKOV), a server computer, and a number of SwarmBang robots. Each SwarmBang robot is a compact two-wheeled differential-drive robot with two stepper motors. A marker plate is mounted on the top of a robot holding five passive infrared reflective balls (10 mm) for being tracked by the motion capture system. SwarmBang robot is equipped with a wireless communication module (NRF24L01) to receive motion commands from the server computer (see Supplementary Note 11 for detailed descriptions of SwarmBang robots).

Citation Zheng Z, Tao Y, Xiang Y, et al. Nested interaction network enhances responsiveness in collective behavior[J]. Communications Physics, 2026.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001699681000003

Thrust-coefficient-coupled extended state observer for robust control of a coaxial omnidirectional tiltrotor aircraft

Keywords

Omnidirectional tiltrotor; Geometric control; Extended state observer; Human-robot interaction; Physical interaction

Abstract

A coaxial omnidirectional tiltrotor aircraft (COTA) exhibits strong coupling among thrust generation, attitude dynamics, and external disturbances, particularly during aggressive maneuvers and physical interaction tasks. A conventional extended state observer (ESO) typically treats the commanded control wrench as its known input. However, this assumption becomes problematic for COTAs because the actual control wrench depends on actuator states and thrust coefficients and may deviate significantly from the commanded input due to actuator dynamics and thrust-coefficient variations. To address this input mismatch, this paper proposes a thrust-coefficient-coupled extended state observer (TCESO). The TCESO reconstructs the observer-side input in real time from measured actuator states together with an online estimate of the thrust coefficient. This design ensures that the observer is driven by a term that more closely approximates the actual physical input, thereby yielding a more accurate internal model. To improve robustness and avoid dual disturbance compensation, a de-coupled strategy is adopted: the instantaneous thrust-coefficient estimate is used exclusively within the observer, whereas a filtered and subsequently frozen value identified during takeoff is used for control allocation. Real-world flight experiments, including aerodynamic-disturbance rejection, human-robot interaction, and physical interaction, demonstrate that the proposed TCESO framework provides better or more balanced performance than both a baseline SE(3) controller and a conventional ESO-based controller, with the clearest advantages appearing in attitude-critical and interaction-rich scenarios.

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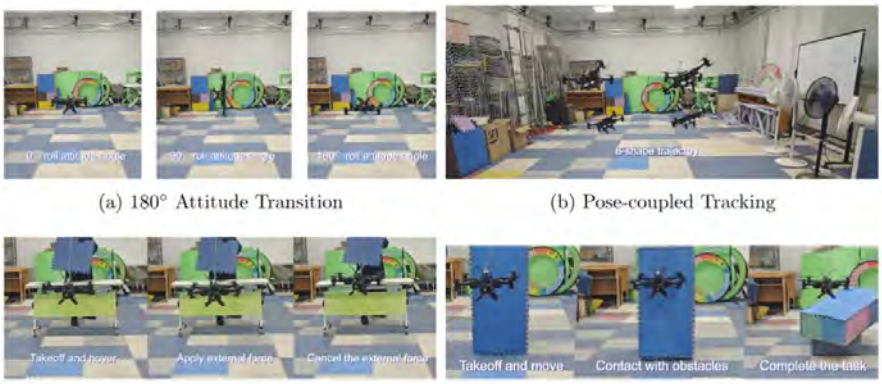

(a) 180° Attitude Transition (b) Pose-coupled Tracking

(c) Human–robot Interaction with Rigid Rods (d) Physical Interaction with Obstacles

Fig. 3. Prototype and snapshots of the conducted experiments. (a) 180° attitude-transition flight. (b) Pose-coupled trajectory-tracking flight. (c) Human–robot interaction with rigid rods. (d) Physical interaction with obstacles. The supplementary video provides representative demonstrations of the four scenarios and highlights the corresponding flight and interaction behaviors. Additional photos and videos are available at https://youtu.be/6GRc5nWE74E.

How NOKOV Contributes to the Research

All tests are performed in a motion-capture environment equipped with a Nokov optical tracking system that provides full-pose measurements. Low-level sensing and actuation are handled by an STM32F407 microcontroller, which samples the BMI088 IMU, drives the motors and tilt servos, and manages low-level communication at 1 kHz. High-level modules, including state estimation, trajectory generation, thrust-coefficient estimation, and control computation, run on the Khadas VIM4 onboard computer at 500 Hz.

Citation Guan R, Hao N, He F, et al. Thrust-Coefficient-Coupled Extended State Observer for Robust Control of a Coaxial Omnidirectional Tiltrotor Aircraft[J]. Aerospace Science and Technology, 2026: 112371.

Link

https://ev.publinks.top/app/doc/?docid=cpx_M7c45ad0819dce5fa109M7ac71017816360&pageSize=25&index=1&searchId=5b16c63ca6c745bea0f4c449c4d3eaa9&resultsCount=1&usageZone=resultslist&usageOrigin=searchresults&searchType=Quick

Anti-singular control of a hybrid-motion vehicle and experimental validations for its applicability in micro-sized transportation scenarios

Keywords

Motion tracking; Disturbance estimation; Actuator saturation; Singularity avoidance; Micro-sized transportation

Abstract

Ground vehicles are vital in modern transportation systems due to their mobility and accessibility. This paper focuses on how to utilize control techniques to achieve economical and efficient transportation at the micro-sized level. Our main goal is to achieve smooth and precise motion tracking for our hybrid-motion vehicle to further make it applicable for micro-sized transportation scenarios. To enhance the tracking precision of the Ackermann steering mode, we first propose a disturbance estimator design that provides knowledge of the model uncertainty within a fixed time. To avoid having excessively large steering angles when there is a lack of proper speed, a new auxiliary variable that describes the steering tendency is defined to handle input saturation when there is speed-steering coupling. The concept of steering singularity is then defined to illustrate when it is necessary to perform inter-mode switching. Adaptive algorithms are developed to quantify the steering singularity issue and provide smooth commands for Ackermann-differential transitions. To validate the control scheme's capability in micro-sized transportation, hardware-in-the-loop experiments are conducted for transportation-related tasks including fixed-point tracking (cargo delivery), dual circles tracking (constant speed following for pedestrians and cyclists) and complex nonlinear trajectories (last-mile delivery in complex environments). The results demonstrate that the hybrid-motion vehicle can be a reliable part of micro-sized transportation, and provided insights for how to model the vehicle's behavior in practice.

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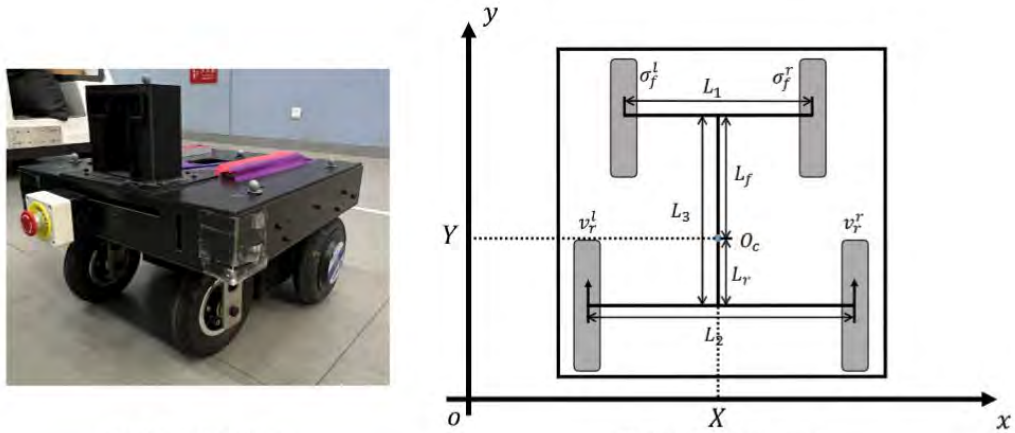

(a) Physical platform (b) Theoretical structure

Fig. 1. Illustration of the hybrid-motion vehicle's structure.

How NOKOV Contributes to the Research

Similarly, it is essential to analyze the estimator's performance in HIL experiments. When the proposed HCE scheme is employed, the state estimation error is recorded in Fig. 11. The result for tasks with fixed points are quite similar, with a static state estimation error of around 0.001 when \$t \to +\infty\$. Although the NOKOV motion capture feedback also contains noise, it also took the HCE scheme a fixed time of 2.5 s to achieve \$\sqrt{\widetilde{X}^2+\widetilde{Y}^2} \leq 0.007\$ for complex and dynamic references.

Citation Fei Y, Wang Y, Zhen W, et al. Anti-singular control of a hybrid-motion vehicle and experimental validations for its applicability in micro-sized transportation scenarios[J]. Transportation Research Part C: Emerging Technologies, 2026, 188: 105698.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001755456800001

Density-Driven Progressive Shape Formation for Swarm Robots in Dynamic Environments

Keywords

Swarm robotics, shape formation, density-driven, shape transformation, local perception.

Abstract

This letter presents a novel density-based control framework for shape formation in swarm robotic systems, operating exclusively on local perception without requiring communication or identity recognition among robots and targets. Inspired by Smoothed Particle Hydrodynamics (SPH), each robot estimates a local spatial density using kernel functions and regulates its motion based on the gradient of a constructed target density field. Unlike existing methods that depend on global coordination or explicit target assignments, the proposed approach enables fully distributed shape formation through local density regulation alone. By adjusting the reference density, the system supports autonomous scaling in both the number of robots and the geometric size of the target shape, seamlessly transitioning among shape-surrounding, double-layer contour, and boundary-conformal formations. A composite control law integrates density-driven forces, repulsive interactions for collision avoidance, and damping for dynamic stability. The effectiveness and robustness of the method are validated through extensive simulations and physical experiments with 50 robots under a motion capture laboratory setup. Results demonstrate the scalability, resilience, and practicality of the approach for decentralized swarm shape formation.

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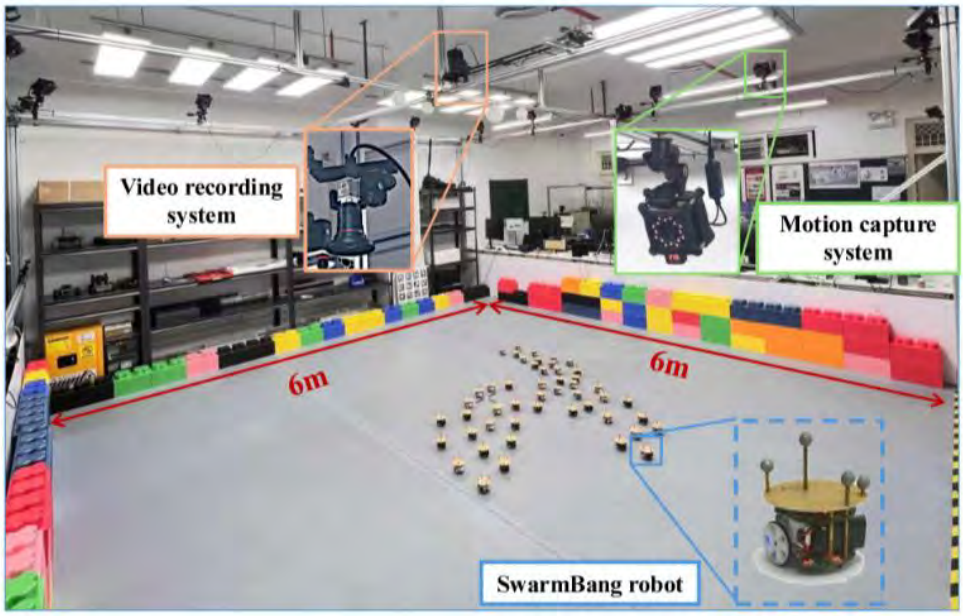

Fig. 5. SwarmBang swarm experimental validation platform.

How NOKOV Contributes to the Research

*The SwarmBang swarm experimental validation platform consists of up to about 100 desktop robots (each with a size of 60 mm × 60 mm × 60 mm), a **NOKOV** motion capture system, a video recording system, and a server (Fig. 5) .*

Citation Xiang Y, Song J, Zheng Z, et al. Density-Driven Progressive Shape Formation for Swarm Robots in Dynamic Environments[J]. IEEE Robotics and Automation Letters, 2025, 11(2): 1186-1193.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001638044400010

Real-time Motion Segmentation with Event-based Normal Flow

Abstract

Event-based cameras are bio-inspired sensors with pixels that independently and asynchronously respond to brightness changes at microsecond resolution, offering the potential to handle visual tasks in challenging scenarios. However, due to the sparse information content in individual events, directly processing the raw event data to solve vision tasks is highly inefficient, which severely limits the applicability of state-of-the-art methods in real-time tasks, such as motion segmentation — a fundamental task for dynamic scene understanding. Incorporating normal flow as an intermediate representation to compress motion information from event clusters within a localized region provides a more effective solution. In this work, we propose a normal flow-based motion segmentation framework for event-based vision. Leveraging the dense normal flow directly learned from event neighborhoods as input, we formulate the motion segmentation task as an energy minimization problem solved via graph cuts, and optimize it iteratively with normal flow clustering and motion model fitting. By using a normal flow-based motion model initialization and fitting method, the proposed system is able to efficiently estimate the motion models of independently moving objects with only a limited number of candidate models, which significantly reduces the computational complexity and ensures real-time performance, achieving nearly a 800× speedup in comparison to the open-source state-of-the-art method. Extensive evaluations on multiple public datasets fully demonstrate the accuracy and efficiency of our framework. Our code is released at https://github.com/NAIL-HNU/EvMotionSeg to facilitate further research in this field.

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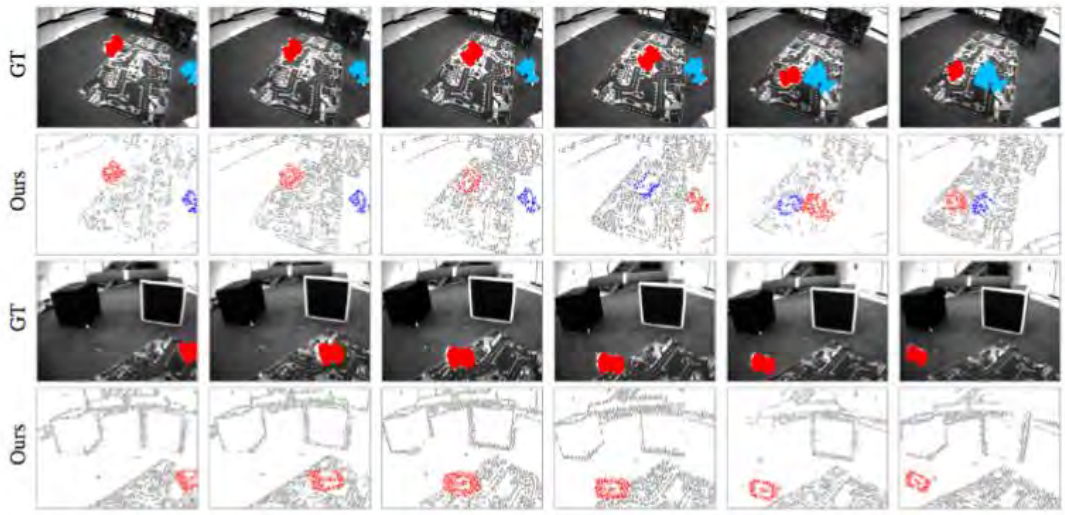

Fig. 5: *Segmentation results on the EVIMO dataset* [8], *on sequences Table (rows 1-2) and Boxed (rows 3-4).* Time runs from left to right. The grayscale images are used for visualization only. The color of each label is determined by the number of normal flow associated with it, meaning that the label color for the same IMO may vary at different time. The ground truth mask is not perfectly aligned with the IMOs in the grayscale image due to the presence of motion blur.

How NOKOV Contributes to the Research

To evaluate the system performance, we conduct evaluations on three publicly available event-based motion segmentation datasets, with key characteristics detailed in Tab. I. The Extreme Event Dataset (EED) is one of the first open-source datasets for IMO detection and tracking. Each sequence contains camera ego-motion and IMOs, collected in laboratory environments featuring controlled high dynamic range conditions. EVIMO , also captured in laboratory settings but under better illumination, features sequences with up to three IMOs and provides dense segmentation masks for evaluation. Unlike the aforementioned datasets, EMSGC provides outdoor sequences containing non-rigid IMOs (e.g., pedestrians), on which we conduct qualitative comparisons with the EMSGC algorithm. In addition, we record a small number of sequences in a room equipped with the NOKOV Mars26H

Citation Zhong S, Ren Z, Zhu X, et al. Real-time Motion Segmentation with Event-based Normal Flow[J]. arXiv preprint arXiv:2602.20790, 2026.

Link

https://ev.publinks.top/app/doc/?docid=cpx_M66f3009919cd20bb134M7d8e1017816518

Precise aggressive aerial maneuvers with sensorimotor policies

Keywords

OPTIMIZATION; ODOMETRY

Abstract

Precise aggressive maneuvers with lightweight onboard sensors remain a key bottleneck in fully exploiting the maneuverability of drones. Such maneuvers are critical for expanding the systems' accessible area by navigating through narrow openings in the environment. One of the most relevant problems is aggressive traversal through narrow gaps with quadrotors under constraints in the special Euclidean group of three dimensions [SE(3)], which requires the quadrotors to leverage a momentary tilted attitude and the asymmetry of the airframes to navigate through gaps. Here, we achieved such maneuvers by developing sensorimotor policies directly mapping onboard vision and proprioception into low-level control commands. The policies were trained using reinforcement learning (RL) with end-to-end policy distillation in simulation. We mitigated the model-free RL's exploration challenge on the restricted solution space with an initialization strategy leveraging trajectories generated by a model-based planner. Careful sim-to-real design allowed the policy to control a quadrotor through narrow gaps with low clearances and high repeatability. For instance, the proposed method enabled a quadrotor to navigate a rectangular gap at a 5-centimeter clearance, tilted at an orientation up to 90 degrees, without knowledge of the gap's position or orientation. Without training on dynamic gaps, the policy could reactively servo the quadrotor to traverse through a moving gap. The proposed method was validated on challenging tracks of narrow, closely placed gaps. The flexibility of the policy learning method was demonstrated by developing policies on geometrically diverse gaps without relying on manually defined traversal poses and visual features.

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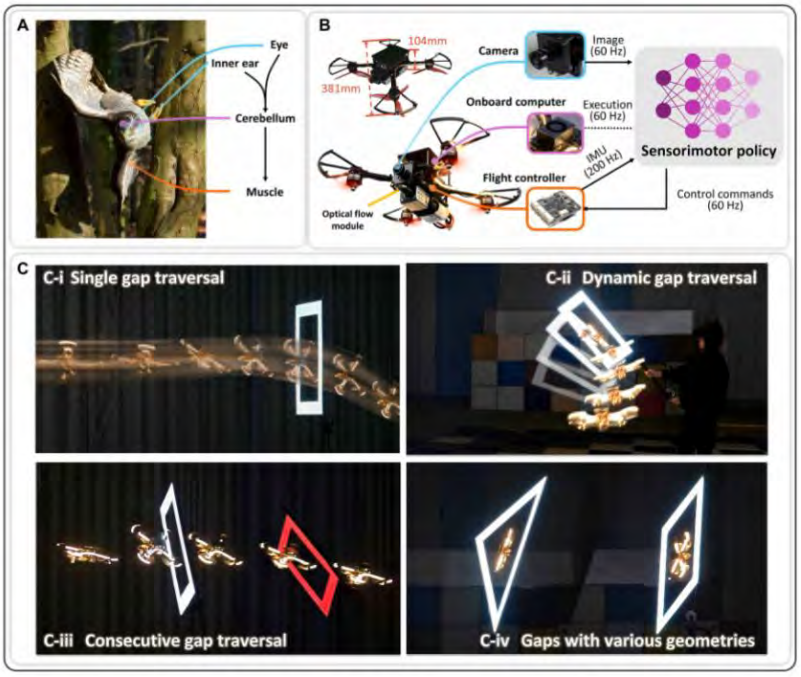

Fig. 1. Working principle and system implementation. (**A**) Illustration of a goshawk precisely executing aggressive maneuvers through a gap in deciduous trees. This behavior is guided entirely by its embodied perception system. The bird's cerebellum integrates visual input from its eyes with proprioceptive signals from its vestibular system to generate precise motor commands for gap navigation. (**B**) Illustration of the quadrotor platform equipped with a sensorimotor policy for precise aggressive flight using only onboard sensing. The policy integrates the visual sensing and proprioception that directly generate low-level control commands without explicit intermediate interfaces, such as state estimates and reference trajectory. (**C**) Key capabilities demonstrated by the proposed method through the quadrotor system: (i) single gap traversal, (ii) dynamic gap traversal, (iii) consecutive gap traversal, and (iv) traversal through geometrically diverse gaps.

How NOKOV Contributes to the Research

To contextualize the performance and validate capabilities beyond existing systems, we implemented two representative baselines from prior work: The baseline 1 approach [Wang et al. (12)] uses a known gap position and pose to formulate trajectory optimization incorporating SE(3) geometric and dynamical constraints. A reference trajectory is generated and tracked by a low-level controller with full-state feedback from an external motion capture system; the baseline 2 system [Falanga et al. (14)] achieves narrow gap traversal without external localization or prior knowledge of gap orientation. It uses vision-inertial fusion for state estimation, with gap corners detected via rectangle and point detection for perspective-n-point pose estimation. A specialized trajectory generation scheme enables rapid online replanning and traversal through gaps with up to a 45° orientation and 8-cm clearance (14). The localization method in this system achieves higher accuracy as the quadrotor approaches the gap.

Citation Wu T, Xu G, Wang Z, et al. Precise aggressive aerial maneuvers with sensorimotor policies[J]. Science Robotics, 2026, 11(115): eaeb0180.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001788798200002

An impact-aware implicit planning and control framework for cooperative aerial transportation

Keywords

Cable-suspended aerial transportation, Variational integrator, Complementary constraints, Hybrid dynamics

Abstract

Cooperative aerial transportation involves complex hybrid dynamics, such as cable tensioning and ground interaction, which are often simplified in existing literature. To address these non-smooth cases, this paper proposes a unified planning and control framework based on impact-aware implicit integration. By modeling the system using multibody dynamics in maximal coordinates, we employ a complementary constrained variational integrator derived from a modified Hamilton's principle. This approach naturally resolves impact forces without the need for explicit mode switching. For the critical payload take-off phase, a time-optimal planning method incorporating contact and friction dynamics is developed. Furthermore, a centralized implicit controller, solved via customized primal-dual interior point method, is designed with input-to-state stability guarantee. Compared with state-of-the-art algorithms, the proposed approach demonstrates superior tracking ability in the gravity direction and robustness against impact disturbances. The framework is validated through real-world experiments, confirming its capability for full-pose trajectory tracking.

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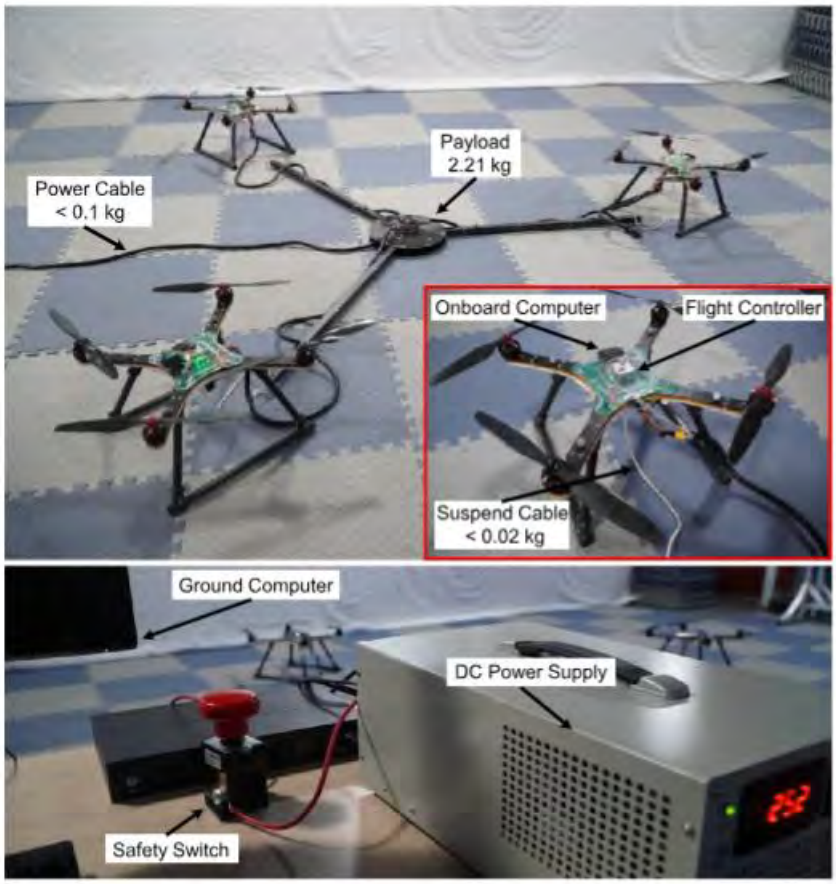

Fig. 14. Hardware setup of the cooperative transportation system.

How NOKOV Contributes to the Research

The total mass of airborne power supply cable and suspend cable is < 0.2 kg, which is less than 10% of the total system mass and therefore considered negligible. Computational tasks (implicit controller) are executed on a ground station computer (Intel Core i7-12700 CPU, 32 GB RAM), while the onboard computers handle only communication relaying. The ground computer is connected to all the onboard computers via ethernet wire and network switch. Under such implementation, system-wide operation and inter-device communication are managed seamlessly within the ROS 2 Humble environment, utilizing the µXRCE-DDS bridge to interface directly with the CUAV V5+ flight controller. All system states are measured by a Nokov Mocap system. Additional experimental parameters are listed in Table 4.

Citation Cui Y, Li T, Chen H, et al. An impact-aware implicit planning and control framework for cooperative aerial transportation[J]. Control Engineering Practice, 2026, 174: 107037.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001766697400001

Human-Centric Motion Planning in Crowded Spaces: A Structured Neural Circuit Approach with Social Interaction-Awareness

Keywords

Crowd navigation; Deep reinforcement learning; Neural circuit policies; Socially-aware robot

Abstract

Safe and socially compliant navigation in dense human crowds presents a critical challenge for mobile robots, requiring consideration for not only physical safety but also human psychological comfort. However, current approaches often overlook the social impact of a presence of the robot on nearby people and fail to adequately model the temporal nature of navigation tasks. This limits their robustness in dynamic and uncertain environments. To address these limitations, this paper proposes a novel social navigation algorithm: Structured Neural Circuit Policies with Proximal Policy Optimization (SNCP-PPO) algorithm. First, we design a biologically-inspired Actor-Critic network that uses ordinary differential equations (ODEs) to model the continuous-time evolution of states. This captures temporal causality in interactions and significantly enhances the decision-making robustness of the model. Second, we establish a human social space model and introduce a social pressure index to quantify the discomfort caused by the robot. By integrating this index into the reinforcement learning reward function, the robot learns to minimize its social intrusion while maintaining navigation efficiency. Experimental results in both simulated and real-world settings demonstrate that SNCP-PPO algorithm achieves a 93% to 95% success rate in dynamic environments with 10 to 20 people. It also outperforms baseline algorithms and generates more socially compliant trajectories.

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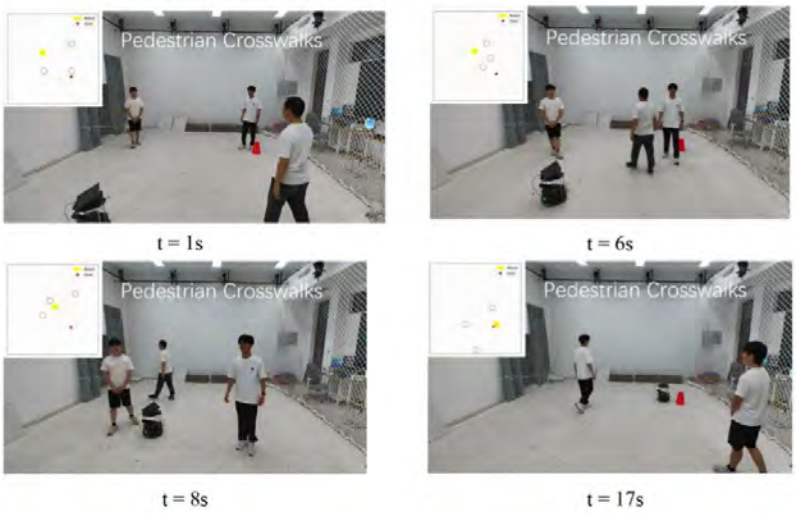
Fig. 11 Experimental setup. The motion capture system is placed above the experimental field. The red bucket is the target position of the robot. The robot and the target position are randomly placed at the beginning of the experiment



How NOKOV Contributes to the Research

As shown Fig. 10, the robot uses the NOKOV motion capture system to locate the robot and obtain the robot and human position. The positions of the Turtlebot robot and humans are tracked by a motion capture system. This system transmits the acquired kinematic data via a wired network to a central computer, which serves as the ROS master. On this computer, the SNCP-PPO algorithm processes the positional information to generate control commands, defined as linear and angular velocities.

Citation Ao T, Li H, Tian Y, et al. Human-Centric Motion Planning in Crowded Spaces: A Structured Neural Circuit Approach with Social Interaction-Awareness[J]. International Journal of Social Robotics, 2026, 18(3): 52.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001718853500001

Visual and Visual-Inertial SLAM Based on Enhanced Deep Learning Features and Motion Smoothness Constraints

Keywords

computer vision; deep learning; mobile robot; visual simultaneous localization and mapping; visual-inertial simultaneous localization and mapping

Abstract

It is highly challenging to ensure accuracy and robustness of simultaneous localization and mapping (SLAM) algorithms with rapid camera movements and drastic viewpoint changes. In these scenarios, feature extraction, feature matching, and tracking become very difficult. To address this issue, visual and visual-inertial SLAM based on enhanced deep learning features and motion smoothness constraints is proposed in this work. A lightweight convolutional neural network is integrated into geometry-based visual and visual-inertial SLAM to enhance the quality of extracted features. Next, feature matching and tracking are respectively improved. The rotation angle information is computed and integrated for the extracted deep learning features. Based on the statistical results of rotation angle information, the feature matching point pairs with low accuracy are eliminated. Motion smoothness constraints are introduced to the tracking process using a grid-based motion statistics method, thereby enhancing the performance of SLAM tracking. The performance of the proposed SLAM is evaluated through dataset experiments and robot experiments in real-world scenarios. The outcomes demonstrate favorable performance of the proposed SLAM compared to other state-of-the-art algorithms.

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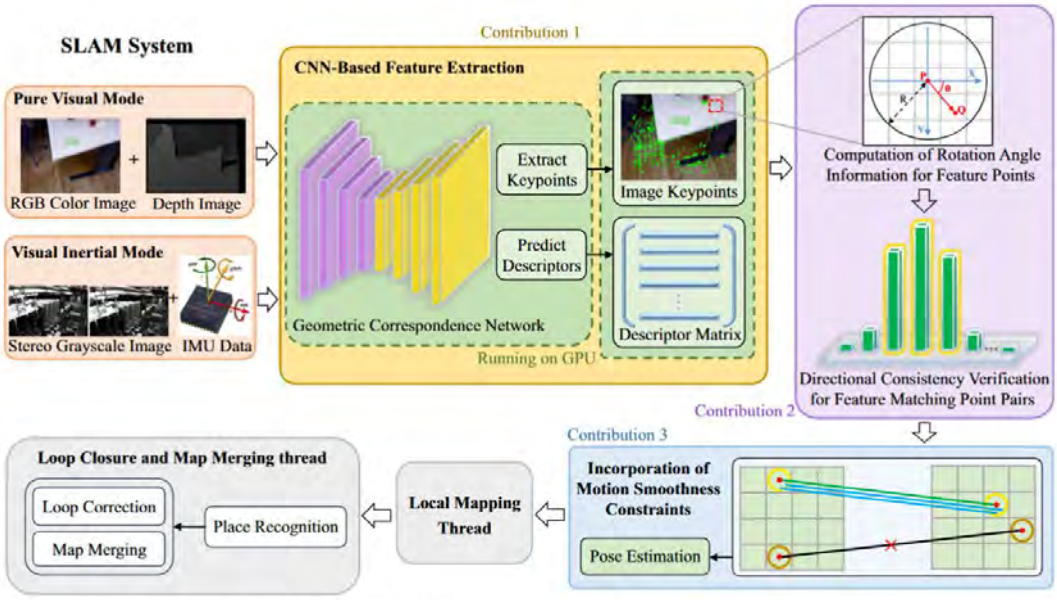

FIGURE 1 | The overall framework of the proposed SLAM approach.

How NOKOV Contributes to the Research

Moreover, this camera incorporates a built-in IMU operating at 200 Hz. A NOKOV optical 3D motion capture system is installed at the experimental site to track movement. It is worth mentioning that the time synchronization between the RealSense D455 and the motion capture system is achieved through software timestamp alignment, and the external parameter calibration is accomplished using the trajectory evaluation software.

Citation Jiang M, Ma L, Zhang M, et al. Visual and Visual-Inertial SLAM Based on Enhanced Deep Learning Features and Motion Smoothness Constraints[J]. Advanced Intelligent Systems, 2026: e202501455.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001753511500001

Square Cupola AprilTag: A High-Precision Fiducial Marker for Pose Estimation Based on Accuracy Experiments of AprilTag

Keywords

pose estimation, fiducial marker, UAV target tracking

Abstract

Precise pose estimation is crucial for unmanned aerial vehicles (UAVs). Fiducial markers provide a straightforward solution without relying on external systems. However, the detection of these markers is limited to specific rotation angles, and their localization accuracy requires enhancement. To overcome these limitations, we propose the square cupola AprilTag, which enables detection over a broader range of angles due to its three-dimensional structure. The pose estimation results of various markers are optimally fused based on accuracy experiments of the standard AprilTag. The experimental results demonstrate a significant reduction in pose errors and robustness in reflective environments. The effectiveness of our method is further validated in UAV tracking scenarios.

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Fig. 5. Overview of the experimental setup.

How NOKOV Contributes to the Research

For the AprilTag accuracy experiments, the monocular camera utilized to detect markers is the Amovlab G1 equipped with a gimbal. It is a fish-eye camera and collects data at 11.3 M pixels and 120 fps. The computer is Amovlab Allspark 2, which is developed based on NVIDIA Jetson NX. Its RAM is 8G LPDDR4x at 1600 MHz. The ground truth poses of the marker and the camera gimbal are obtained from the NOKOV motion capture system. Its position error and orientation error are less than 0.1 mm and 0.1° respectively. The square cupola shaped frame of our marker is produced by 3D printing. Figure 5 shows the experimental scene.

Citation Yang H, Sun Y, Huang J, et al. Square Cupola AprilTag: A High-Precision Fiducial Marker for Pose Estimation Based on Accuracy Experiments of AprilTag[C]//International Conference on Aerospace System Science and Engineering. Singapore: Springer Nature Sing

Link https://link.springer.com/chapter/10.1007/978-981-95-6366-1_12

A UGV-UAV Cooperative Navigation Framework: Obstacle-Aware Planning for Perception-Limited UGVs Enhanced by LiDAR-Based UAV Mapping

Keywords

UGV-UAV coordination · Multi-UGV navigation · LiDAR-based SLAM · Motion capture-based localization · Obstacle avoidance

Abstract

An integrated UGV-UAV cooperative navigation framework is proposed to support multiple unmanned ground vehicles (UGVs) operating with limited onboard perception. In this system, a LiDAR-equipped unmanned aerial vehicle (UAV) autonomously explores unknown environments and builds a global occupancy map through simultaneous localization and mapping (SLAM). The UGVs, lacking their own perception capabilities, rely on external motion capture systems for precise localization and receive the shared map information from the UAV to perform trajectory planning with obstacle avoidance. To ensure safe and efficient navigation, the UAV dynamically assesses potential collision risks along UGV-predicted paths and provides targeted perception support by visiting critical areas. A vehicle routing problem with time windows (VRPTW) model is formulated to optimize the UAV's assistance schedule. The framework is validated through real-world indoor experiments, demonstrating its efficacy in enabling reliable multi-UGV navigation under constrained sensing conditions. The proposed system is particularly well-suited for structured environments such as warehouses, laboratories, and testbeds.

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Fig. 6. Experiment setup with UAV, multiple UGVs, and optical motion capture system

How NOKOV Contributes to the Research

An indoor-oriented heterogeneous UGV-UAV collaborative navigation framework is developed to facilitate coordination among multiple unmanned ground vehicles (UGVs) in environments with limited perception. The system consists of three core components: a LiDAR-equipped quadrotor UAV with onboard SLAM capabilities, a team of four-wheeled differential-drive UGVs, and a NOKOV motion capture (MoCap) system that provides high-frequency global localization. The deployment setup is depicted in Fig. 1, and the overall system architecture is illustrated in Fig. 2.

Citation Xie H, Duan X, Zhao F, et al. A UGV-UAV Cooperative Navigation Framework: Obstacle-Aware Planning for Perception-Limited UGVs Enhanced by LiDAR-Based UAV Mapping[C]//International Conference on Autonomous Unmanned Systems. Singapore: Springer Nature Singa

Link https://link.springer.com/chapter/10.1007/978-981-95-7648-7_16

PerchRL: Vision-Based Agile Perching on Inclined Platforms under Rapid and Irregular Motion

Keywords

Vision-Based Perching, Quadrotor, Reinforcement Learning

Abstract

Autonomous vision-based perching of quadrotors on moving inclined platforms is critical for air-ground collaboration but remains challenging due to the limited field of view (FOV). In this paper, we propose PerchRL, a reinforcement learning (RL) framework for vision-based agile perching on inclined platforms under rapid and irregular motion. Specifically, we employ a two-stage learning strategy consisting of state-based pre-training followed by vision-based fine-tuning. To improve generalization across diverse platform motions, we employ randomized platform trajectories to prevent overfitting and temporal augmentation methods to capture latent motion patterns from historical observations. During vision-based fine-tuning, a hybrid learning framework consisting of visibility-aware state augmentation and active perception rewards is presented to improve robustness under intermittent visual loss. Extensive simulation and real-world experiments demonstrate the feasibility, stability, and real-time performance of PerchRL, while successful deployment across distinct quadrotor platforms further validates its adaptability. The source code will be released to benefit the community.

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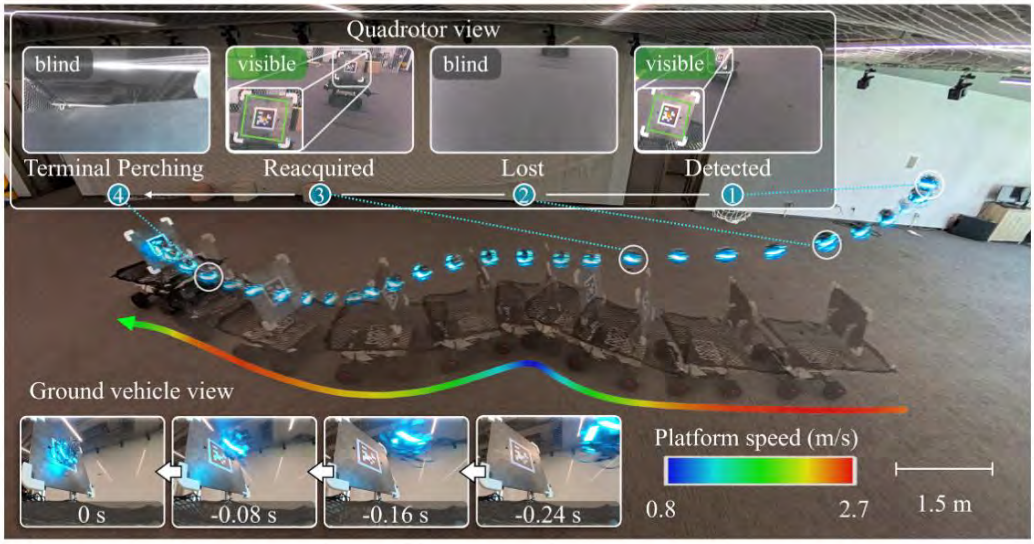

Figure 1: Real-world demonstration of PerchRL. The ground vehicle equipped with a 70° inclined platform tracks a randomly generated spline trajectory with periodically varying forward speed. The top and bottom inset images show additional views of the aerial perching process from cameras mounted on the quadrotor and ground vehicle, respectively.

How NOKOV Contributes to the Research

The tested Crazyflie weighs 31.1 g and has a thrust-to-weight ratio of approximately 1.53. Accurate state estimates of both the quadrotor and the platform are provided by an NOKOV motion capture system at 100 Hz and transmitted to an offboard computer, where a state-based policy is deployed for static inclined perching experiments. The output CTBR commands are sent to the Crazyflie via the official Crazyswarm API [35] and executed by the onboard low-level PID controller for real-time control of the quadrotor. In this experiment, Velcro is used to secure the quadrotor to the platform after perching.

Citation Lu Z, Liu Z, Li H, et al. PerchRL: Vision-Based Agile Perching on Inclined Platforms under Rapid and Irregular Motion[J]. arXiv preprint arXiv:2606.03441, 2026.

Link https://arxiv.org/abs/2606.03441

变形轮爪构型无人平台结构优化与运动学分析

关键词

陆空无人平台；变形轮设计；轮爪运动；运动学分析

摘要

针对陆空两用无人平台的在复杂楼宇行驶环境中难以穿行且越障能力有限的问题，提出了一种具有大展开比特征的高 通过性变形轮爪构型无人平台，可从圆轮状态切换至轮爪状态。然后建立以变形轮变形触发力矩和压力角均值最小为目标的 结构参数优化模型，采用二次序列规划法(SQP)对该约束优化问题进行求解。此外，基于对单个变形轮的周期性运动分析， 搭建了无人平台整机运动学模型，并通过多体动力学仿真和动作捕捉试验对理论模型进行了验证。结果表明，相较于优化前 的初始结构，优化后的变形触发力矩降低了 20%，压力角均值下降了 38.5%，优化后的触发力矩理论值与仿真结果的误差仅 为 6.25%。根据优化结果得到的无人平台整机位移与速度曲线与仿真及试验结果的趋势基本一致，变形轮爪式无人平台在展 开比为 2.0 时可越过高度为 500 mm 的障碍物，为后续高通过性无人平台动力学模型和轨迹优化提供了理论基础。

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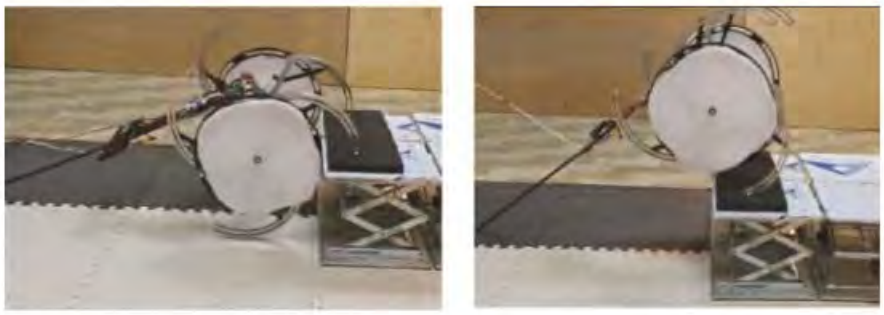

(a) 开始越障　　(b) 通过越障

图 21　无人平台轮越过 450 mm 障碍图

NOKOV 度量动作捕捉在研究中的应用摘录

作为对照的无人平台运动样机试验由于轮心的位移和速度变化量难以采集，采用 NOKOV 光学三维动作捕捉系统，如图 17 所示在样机上设置反光点，1 号反光点设置在轮爪末端，二号反光点设置在变形轮中心位置，监测轮心运动，3 号反光点设置在轮圈边缘，和 1 号反光点一同用来动态测量展开比，4 号反光点安装在无人平台质心，监测整机运动状态。使用多个高速相机记录反光点的位移和速度情况。

引用格式 刘建峰,孟庆凯,舒用杰,等.变形轮爪构型无人平台结构优化与运动学分析[J].机械工程学报,2025,61(19):91-100.

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多 UAV 和 UGV 协作监测系统路径规划研究

关键词

异构机器人；路径规划；持续监测；基尼不纯度；路径随机性

摘要

空地异构机器人系统由无人机和地面车组成，通过两者相互协作完成持续监测任务可以提高工作效率、解决无人机续航能力不足的问题。在该异构机器人系统中，地面车可以为无人机进行补能，保证监测任务的持续性。由于周期性的监测路径极易发生监测规律信息的泄露，因此，提高无人机监测路径的随机性具有重要意义。针对上述问题，本文从兼顾任务持续性和路径随机性的角度出发，研究了多 UAV\&UGV 协作监测系统的路径规划问题。

首先，本文充分考虑无人机能量、地面道路网络、目标点等待时间、空-地汇合时间等约束，引入了基尼不纯度的概念，从节点的监测频率和监测路径的随机性两个方面综合构建了路径的优化指标，分别建立单 UAV\&UGV 和多 UAV\&UGV 的空-地协作持续监测路径规划模型。

然后，基于所建立的空地协作监测路径规划模型，利用蚁群算法求解，得到目标点平均访问间隔最短且路径安全性最佳的无人机监测路径和地面车补能路径。通过与其他算法比较，说明了蚁群算法具有更快的搜索速度和运行效率。

最后，开展了室内环境中单 UAV\&UGV 协作监测系统的路径规划实验，通过将仿真和实物实验得到的路径结果作对比分析，进一步验证了本文路径规划方法的可行性和有效性。本文提出的方法为求解其他领域的空地协作路径规划问题提供了理论依据和实际经验参考。

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图 5.2 实验环境

NOKOV 度量动作捕捉在研究中的应用摘录

为了克服 GPS 定位系统无法在室内完成工作，并且定位精度不够高等问题，本文物理实验利用 Nokov 光学三维动作捕捉系统，通过分布在三维空间中的动捕相机，对室内环境的捕捉区域实施覆盖。动捕相机可以发射一定波长的红外光，对贴在无人机和地面车表面的反光标志点进行三维空间位置的实时精确捕捉，精度可达到亚毫米级。

引用格式 夏丹.多无人机和 UGV 协作监测系统路径规划研究[D].武汉科技大学，2023.DOI：10.27380/d.cnki.gwkju.2023.000398.

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防爆消防机器人设计与协同控制研究

关键词

防爆消防机器人;履带式底盘;建模;预设性能;协同控制;事件触发;输出反馈;指控平台;

摘要

近年来火灾事故频发,严重影响了消防救援人员和人民群众生命财产安全。从山东金誉大爆炸到响水爆炸、昆山爆燃火灾事故,造成的损失触目惊心。随着应急救援水平的提高,消防机器人已经成为应对火灾事故必不可少的装备,它可以替代消防人员进入易燃易爆、有毒、缺氧、浓烟等高危事故现场,进行探测、搜救、灭火等任务,有效地提升灭火救援效率,最大程度减少消防人员伤亡。然而,现有消防机器人仍存在环境适应性差、可靠性差、协同作业能力不足、统一指控缺失等问题,亟需研制面向火场恶劣环境的智能化、自主化的防爆型消防机器人,提升消防机器人的火场环境适应性和灭火救援效率。因此,本文针对消防机器人面临的上述问题,开展了防爆消防机器人履带式底盘与上装防护设计、机器人运动模型构建与单机预设性能追踪控制、多消防机器人协同控制、一体化指控平台设计等研究。主要研究工作如下: (1)针对火灾现场环境下消防机器人面临的易燃易爆、高温等恶劣工况,以及灭火救援安全作业需求,研究了消防机器人防爆与耐高温防护底盘设计及消防机器人上装防护设计问题。提出了采用高强度、耐冲击材料和机械结构优化设计的新型防爆设计方案,能够将爆炸产生的冲击力分散并引导至底盘两侧,减少对机器人关键部件的冲击。针对机器人耐高温防护问题,根据机体热传导分析并结合对机器人轻量化的需求提出了耐高温防护方案,设计了耐高温温度采集系统,测试了防护方案的性能。进一步,提出了一种由防护层、隔热层和吸热层组成的上装防护设计方案,保障了消防机器人上装机构在火灾现场环境下的安全性。 (2)针对履带式底盘消防机器人控制问题,设计了差速移动方式以控制其偏航角转向运动,根据上装机构和不同型号消防水炮的搭载要求,分析了消防机器人水炮安装位置以及消防机器人作业时水带拖拽的影响及其动态特性,建立了匹配的消防机器人运动学和动力学模型。在此基础上,面向火灾现场环境下消防机器人快速高效控制需求,基于误差状态变换和反步法,设计了消防机器人预设性能位置跟踪控制策略,利用自适应技术在线估计消防机器人系统中的未知参数,增强了消防机器人对于复杂不确定作业场景的适应性。进一步,根据 Lyapunov 稳定性理论,严格证明了所提控制策略的可行性,进而保证闭环系统的位置误差始终满足预设的暂态和稳态性能。最后,通过仿真验证了预设性能控制方法的有效性。 (3)针对目前消防机器人单人-单机操控模式灭火作业效率低、多消防机器人协同作业能力不足的问题,将多消防机器人视作具有共同目标的多智能体系统,实际的消防机器人位置编队、水炮姿态调节等面向现场灭火救援的协同作业任务可以转换为多智能体系统协同控制问题,提出了适用于多机协同作业模式的网络环境下多智能体协同控制方法。具体地,考虑火场环境下消防机器人受到扰动的影响、且机器人系统状态通常难以准确测量,因此,针对具有外部干扰的多智能体系统,提出了基于重置观测器的事件触发分布式协同控制

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策略,设计了一种包含状态重置元件的重置观测器,能够通过状态重置及时消除控制增益的负面影响,从而实现快速精准估计实时状态信息。此外,针对消防现场网络通信带宽受限的问题,为减少智能体间的带宽通信资源消耗,提出了一种新的混杂动态事件触发通信机制并给出了基于混杂系统理论框架的分析与设计方法,与现有的事件触发机制相比,可以显著降低通信频率,提高通信带宽资源利用率。最后,通过仿真验证了重置观测器和混杂事件触发机制的有效性。 (4)针对火灾现场环境下消防机器人状态测量和观测困难、事件触发通信机制需要连续测量状态信息导致过度硬件资源消耗的不足,提出了基于动态输出反馈的多智能体系统混杂动态自触发协同控制方法,构建了包含连续动态和跳变动态的闭环系统混杂系统模型,设计了混杂动态自触发机制,通过引入记忆变量提高了通信事件间的平均触发间隔时间。与事件触发机制被动地等待误差变量超过阈值不同,所提出的自触发通信机制以主动的方式根据当前触发时刻的系统信息提前计算下一触发时刻,减少了实时监测系统误差所造成的资源消耗。最后,在消防机器人设计和多消防机器人协同控制策略设计的基础上,建立了多消防机器人一体化指控平台,完成了面向应用需求的功能模块开发以及与消防机器人平台协议对接,基于搭建的一体化指控平台测试了所提协同控制算法的实际运行效果,进一步,研制的防爆型消防机器人搭载协同控制算法在实际消防现场进行了应用示范。

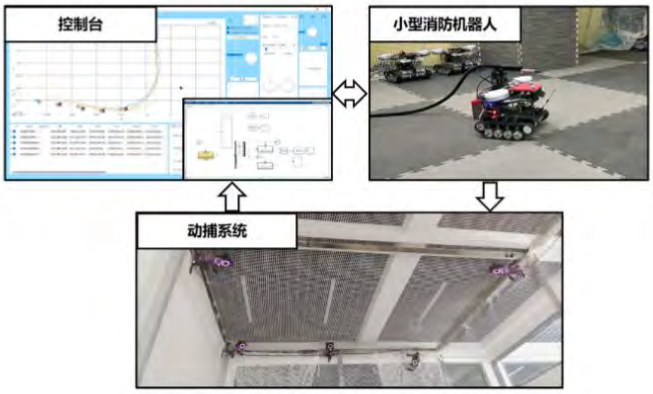

图6-1　消防机器人协同控制实验平台

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> *（2）定位系统与通信网络*
> *平台构建了 RTK、Ultra Wide Band（UWB）两种定位网络，以应对室内室外的两种实验环境，并在室内构建了 NOKOV 动捕系统，用于室内定位、姿态解算、编队控制等算法的研究。*

引用格式　裴文良.防爆消防机器人设计与协同控制研究[D].燕山大学,2025.DOI:10.27440/d.cnki.gysdu.2025.000124.

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GNSS 欺骗干扰下的多智能体系统协同定位导航问题研究

关键词

多智能体系统，GNSS 欺骗干扰，动态协同定位，协同导航

摘要

在现代战争中，快速精确的定位导航能力对智能体的机动性以及整个多智能体系统的协同作战能力产生着重要的作用。在开阔无干扰的任务环境中，使用全球导航卫星系统（Global Navigation Satellite System，GNSS）作为智能体的定位导航系统是当前最好的解决方案。然而当智能体处于电磁干扰区域时，其 GNSS 接收终端极易受到敌方欺骗信号的干扰，从而输出错误的定位导航信息。本文主要研究的是 GNSS 欺骗干扰下的多智能体系统协同定位导航问题，具体工作总结如下：

1）由于 GNSS 欺骗干扰具有很强的隐蔽性，在没有采用有效欺骗检测算法的情况下，智能体通常很难发现自身的定位导航信息因欺骗干扰发生了很大的偏离，从而导致多智能体系统协同作战任务的失败。针对这一问题，本文提出了一种基于信任度评估的欺骗检测算法，通过惯导/里程计的实时输出信息和信任度机制判定 GNSS 输出的定位导航信息是否值得信任，从而实现对 GNSS 欺骗干扰的检测，并对误判具有较好的排除效果。通过仿真验证了所提算法的有效性。

2）对于电磁干扰区域中智能体 GNSS 接收终端受到欺骗干扰的情形，本文在欺骗检测算法的基础上，进一步研究了多智能体系统动态协同定位问题。首先在理论上推导得到了动态协同定位所需要的最少相对距离测量次数；然后提出了一种基于加权半定规划的动态协同定位算法，实现了对目标智能体的准确定位；最后考虑到环境噪声的影响，本文引入极大似然估计使动态协同定位算法具有更强的抗干扰能力。通过仿真验证了所提算法具有较高的定位精度和抗干扰性。

3）在动态协同定位算法的基础上，航位推算系统能保证智能体在短时间内具有较高精度的定位导航能力，但长时间的运行仍存在误差发散的风险。针对这一问题，本文提出了一种基于最优权重分配的协同导航算法，通过扩展卡尔曼滤波和最优权重分配对航位推算信息和相对距离测量信息进行融合，实现了对航位推算系统误差发散的抑制。同时根据可观测性分析理论得到协同导航过程中需要规避的不可观测路径。通过仿真验证了所提算法具备持续高精度的定位导航能力。

4）本文搭建了由无人车、动作捕捉系统和光学相机组成的半实物验证平台。在实验过程中利用动作捕捉系统获取信标无人车的精确位置，同时通过光学相机测量无人车间的相对距离。应用本文所提出的动态协同定位算法和协同导航算法对目标无人车的位置进行实时计算，实验结果验证了算法的正确性与优越性。

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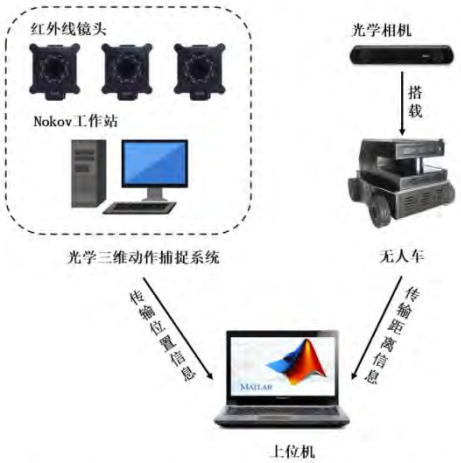

图 5-1 半实物验证平台系统框图及整体搭建示意图

NOKOV 度量动作捕捉在研究中的应用摘录

在本章的半实物实验验证中，将每台无人车粘贴不同方式的特殊反光球体，从而在 Nokov 工作站软件中形成不同的刚体来区分不同的无人车。在光学摄像头识别捕捉到对应的无人车后，Nokov 工作站软件将无人车编号和位置信息一起发送给上位机，减少了后续上位机的计算量。

引用格式 陈鑫明.GNSS 欺骗干扰下的多智能体系统协同定位导航问题研究[D].电子科技大学，2023.DOI：10.27005/d.cnki.gdzku.2023.003289.

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符号网络下的多智能体系统故障检测与协同控制

关键词

多智能体系统，符号网络，故障检测，分布式协同控制

摘要

近年来，多智能体系统协同控制因其在智慧交通、多传感器协同、多机编队等领域的广泛应用，受到了工业界和学术界的共同关注。多智能体系统协同控制的本质是多个自治智能体通过共享信息和相互作用，在群体层面实现一种有序的集体行为，涌现出具有分布式、去中心化特征的群体智能。此外，随着实际多智能体系统日益大型化和复杂化，故障检测技术作为提高系统安全性和可靠性的重要手段，已成为系统协同控制过程中必须要考虑的问题之一。目前，已有的协同控制理论和方法大多聚焦于仅存在合作交互的多智能体系统。然而，除了合作交互，竞争交互在许多实际多智能体系统中也是广泛存在的，例如经济系统、生物系统、社会网络、机器人系统等。这类既存在合作交互又存在竞争交互的网络被称为符号网络。相比于常规合作网络，符号网络下多智能体系统的群体智能涌现机制更为复杂，且对其故障检测机制的研究也更具挑战性。鉴于此，本文以符号网络下的多智能体系统为研究对象，针对其故障检测问题和几类典型的协同控制问题展开理论研究，主要内容包括：

1.研究了符号网络下具有未知输入的多智能体系统的故障检测问题，同时考虑了连续时间动力学模型和离散时间动力学模型。针对连续时间多智能体系统，提出了一种基于相对输出信息的故障检测算法，该算法可以实现对单个执行器故障智能体的检测和隔离，并完成了故障检测算法的分布式实现。针对离散时间多智能体系统，提出了一种基于 H−/H∞未知输入观测器的故障检测算法，该算法既保证了所生成的残差对相应执行器故障的敏感性，又保证了对未解耦的未知输入的鲁棒性。最后，通过数值仿真验证了所提出的故障检测算法的有效性。

2.研究了切换符号网络下多智能体系统的二分一致性控制问题。设计了一种基于异步通信方式的分布式控制器，其中每个智能体仅在由其自身时钟所决定的部分时刻与邻居进行通信。此外，在控制器的设计中还考虑了通信时滞的存在。异步环境和通信时滞的联合影响为二分一致性控制问题的研究带来了挑战。为了克服挑战，首先通过构造混合状态向量将多智能体系统的二分一致性问题等价转换为时变增广系统的渐近稳定性问题；其次，基于矩阵的初等变换，给出了一种有效的参数选择策略，保证了增广系统中系数矩阵的非负性；然后，利用行随机矩阵的相关性质分析了增广系统的收敛性，并得到了系统二分一致性问题可解的充分判据；最后通过数值实例对理论结果进行了验证。

3.研究了拒绝服务攻击（Denial-of-Service，DoS）和异步通信这两类通信受限场景下的符号网络多智能体系统二分跟踪控制问题。对于系统存在 DoS 攻击的情形，考虑了一种通用的 DoS 攻击模型，并利用非负矩阵理论和符号有向图结构平衡理论的相关知识，对系统的收敛性进行了全

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面分析，得到了依赖于攻击频率、攻击持续时间的代数条件。对于异步通信的情形，提出了一种基于异步通信机制的状态反馈控制器，利用子随机矩阵乘积的收敛性分析方法得到了系统实现异步二分跟踪控制的代数条件。数值实例验证了代数条件的正确性。

4.研究了符号网络下多智能体系统的蜂拥控制和二分蜂拥控制问题，其中分别考虑了固定拓扑和切换拓扑的情形。对于蜂拥控制，考虑了一类具有一般拓扑结构的符号网络，即任意两个智能体间允许存在竞争交互。通过求解无限个超随机矩阵乘积的收敛性，得到了固定拓扑和切换拓扑情形下蜂拥控制问题可解的代数条件。对于二分蜂拥控制，分别构造了单调有界的正权函数和负权函数来量化智能体间的合作程度和竞争程度。通过求解无限个子随机矩阵乘积的收敛性，得到了固定拓扑和切换拓扑情形下系统实现二分蜂拥控制的代数条件。数值实例验证了所得结论的正确性。

5.研究了切换符号网络下多智能体系统的二分包含控制问题，同时考虑了二阶动力学模型和广义线性动力学模型。对于二阶多智能体系统，通过适当的模型转换策略，将系统等价转换为一个时变增广系统，然后利用边复合技术分析了时变增广系统的收敛性，并给出了二阶多智能体系统实现二分包含控制的拓扑条件。对于广义线性多智能体系统，通过构造增广有向图，建立了关于系统矩阵谱半径的不等式约束，得到了广义线性多智能体系统实现二分包含控制的拓扑条件。数值例子和无人机平台实验验证了理论结果的正确性。

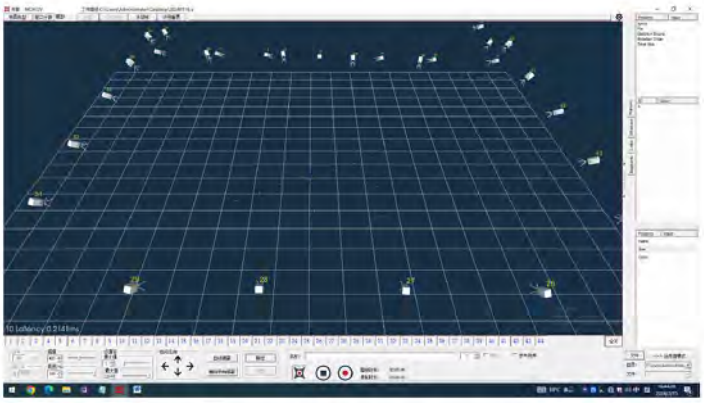

图 6-11 运动捕捉系统软件界面显示

NOKOV 度量动作捕捉在研究中的应用摘录

10 个四旋翼无人机被部署在一个 10×10m2 的正方形区域，该区域由 24 个 Mars4H 相机镜头组成的 NOKOV 光学三维运动捕捉系统覆盖，该运动捕捉系统可以提供 52°×52°的视场角和亚毫米级别的位置数据(误差达到±0.1mm)。图 6-11 为 NOKOV 运动捕捉系统的软件界面显示，从中可以看到运动捕捉系统的覆盖范围与无人机的部署位置。

引用格式 陈璐璐. 符号网络下的多智能体系统故障检测与协同控制[D].电子科技大学，2024.DOI：10.27005/d.cnki.gdzku.2024.000009.

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https://kns.cnki.net/kcms2/article/abstract?v=Uq4Diyda8XAxA1LfLwVF41ADz7Etoc4yGBSfX0qm7DmwYqM1aU2dSPoAO8o6XAtTgcQrTJro3_Bx6CnW5Am-iaS_6uR6zqtBdhp2h7HkENxeEAXjmcxkRg==&uniplatform=NZKPT&language=gb

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复杂环境约束下的飞行航路规划研究

关键词

无人机；战场；侦察；轨迹生成；贝塞尔曲线

摘要

随着战场环境的日益复杂化，实时、精准的信息获取对于战场决策具有决定性影响。然而，传统的无人机侦察路径规划方法常受限于环境复杂性，难以快速且有效地适应动态变化的战场环境。本文提出了一种基于贝塞尔曲线二次优化的无人机侦察路径规划技术，利用贝塞尔曲线的灵活性和几何特性，结合二次优化算法，能够精确构建适应复杂环境的飞行路径。通过在实验室模拟战场环境中进行飞行实验，验证了该路径规划技术的执行效率和安全性。通过对比试验表明：该技术显著提高了无人机的侦察效率和准确性，有效支持了战场中的快速决策和行动，证明了其在实际应用中的可行性和效果。

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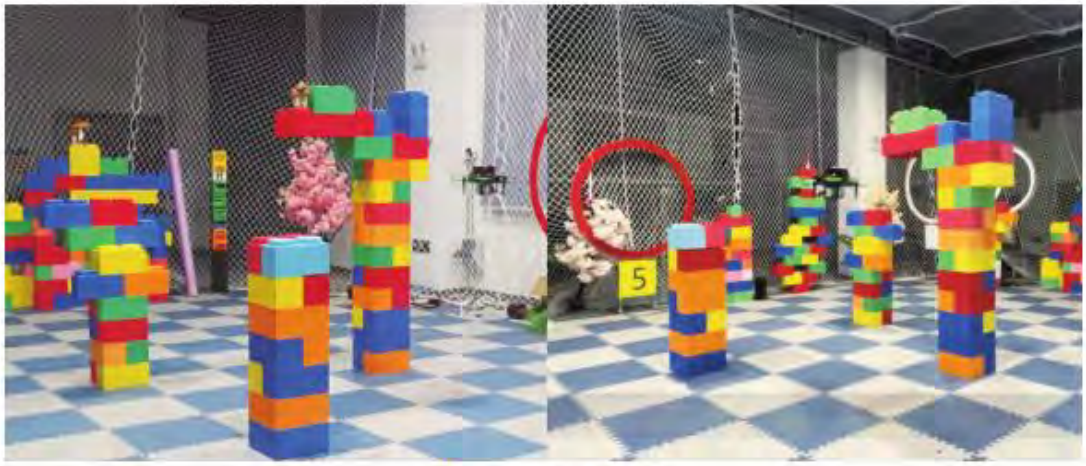

图 2　实验场地实景

Fig. 2　Experimental scene

NOKOV 度量动作捕捉在研究中的应用摘录

实验环境中配备了 Nokov 动捕系统，动态捕捉系统可以 100 Hz 的速度运行，精度高于 1 mm，可以提供四轴飞行器的位置和姿态信息，实验场地如图 2 所示。

引用格式 李徐,董伟,杜泽弘.复杂环境约束下的飞行航路规划研究[J].空天防御,2024,7(04):99-105.

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基于 UWB/INS 的室内组合定位技术研究

关键词

室内组合定位；INS；UWB；NLOS；抗差自适应 UKF

摘要

近年来，随着人们对室内位置服务的需求不断增加，高精度室内定位技术成为定位领域的研究热点。然而，单一定位技术往往难以满足要求。为此，本文以无人车为定位载体，对基于超宽带（Ultra-Wide Band，UWB）和惯性导航系统（Inertial Navigation System，INS）的室内组合定位技术进行研究，旨在充分发挥 UWB 定位精度高和 INS 自主定位的优势，有效克服 UWB 在非视距（Non-Line-of-Sight，NLOS）环境下定位性能较差和 INS 具有累积误差的局限。

本文从测距方法、位置估计算法、NLOS 数据剔除方法三个方面对 UWB 定位技术进行改进。为了省去设备之间的时钟同步工作、减小时钟偏移和响应时间对测距精度的影响，将基于 3 消息的双边双向测距法应用于 UWB 定位。在最小定位系统（三基站）的基础上增加一个基站，采用基于最小二乘法的四次定位法和卡尔曼滤波（Kalman Filtering，KF）进行位置估计，以减少定位过程中的噪声干扰。针对 UWB 定位精度受 NLOS 误差影响严重的问题，重点研究了基于测距变化的 NLOS 数据剔除方法。

为了探讨组合方式对定位性能的影响，本文基于输出校正法，建立了 UWB/INS 松组合定位模型和紧组合定位模型，将常用的状态估计方法 KF、扩展卡尔曼滤波（Extended Kalman Filtering，EKF）分别应用于松组合模型和紧组合模型的数据融合。考虑到 EKF 作为集中式滤波具有容错性差的缺点，本文设计了基于联邦 EKF 的紧组合定位算法。针对系统非线性程度较强时 EKF 一阶线性化误差较大的局限，设计了基于无迹卡尔曼滤波（Unscented Kalman Filtering，UKF）的紧组合定位算法。在此基础上采用方差匹配自适应滤波，重点设计了基于抗差自适应 UKF 的紧组合定位算法，期以减小系统模型误差、噪声协方差误差和状态初值误差对滤波精度的影响。通过仿真验证了算法的有效性。

本文在室内环境下开展了 UWB 定位实验和 UWB/INS 组合定位实验。实验结果表明，基于测距变化的 NLOS 剔除方法的 x 轴、y 轴平均定位精度相对未剔除 NLOS 数据分别提高了 47.2%、41.9%，将最大位置误差从米级降到分米级，与基于接收信号强度指示（Received Signal Strength Indication，RSSI）差值的 NLOS 剔除方法相比具有显著优势；UWB/INS 组合定位实现了 INS 和 UWB 的优势互补，在 NLOS 环境下具有可观的定位精度，在状态初值准确的条件下，基于抗差自适应 UKF 的紧组合定位算法的东向、北向平均定位精度分别达到 0.0372、0.0273，相同运动条件下相对 INS 分别提高了 92.7%、90.4%，相对 UWB 分别提高了 46.6%、62.4%，明显优于基于 KF 的松组合算法和分别基于 EKF、联邦 EKF、UKF 的紧组合算法。

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图 5-2 实验使用的动捕系统场地

NOKOV 度量动作捕捉在研究中的应用摘录

在 NOKOV 三维动作捕捉系统环境下，以松灵机器人（AgileX Robotics） 公司的全能 UGV SCOUT 2.0 为定位载体，使用 Nooploop 公司开发的 LinkTrack 局部定位系统，开展测距试验、静态定位及动态定位实验，验证定位算法在实际应用中的可行性，比较 LOS/NLOS 环境、不同基站数量、不同算法条件下 UWB 系统的定位精度。 NOKOV 动捕系统的定位精度达亚毫米级别，其定位结果可以作为衡量 UWB 系统定位精度的参考值。实验平台和实验环境等将在组合定位实验章节中具体介绍。本节将简要说明 UWB 定位实验过程，重点分析实验结果。

NOKOV 动作捕捉系统是由国内 NOKOV 度量科技公司全自主开发的光学三维动作捕捉系统，主要包括动作捕捉镜头、动作捕捉软件、反光标识点、 POE 交换机等组成部分，如图 5-1 所示。其工作原理是通过布置在空间不同位置的多个动作捕捉镜头获取带有反光标识点的目标物体的二维位置信息，动作捕捉软件 Seeker 根据标定获取的镜头位置信息和镜头获取的二维位置信息计算得到目标物体的三维位置、三维速度和欧拉角等运动信息，从而实现对目标物体运动的实时捕捉。 NOKOV 动捕系统的高精度实时定位追踪能力使其在室内机器人或无人机定位跟踪、多智能体协同控制、人体步态动作捕捉、多刚体结构定位等许多场景中得到应用。由于 NOKOV 动捕系统的定位精度最高可达亚毫米级别，本文将动捕系统的定位结果作为衡量定位精度的参考值，利用其获取的载体运动数据生成 IMU 仿真数据。实验使用的 NOKOV 动捕系统场地、动捕软件界面分别如图 5-2、5-3 所示，场地大小为 7m×7m×7m，核心配置为 16 个 Mars 2H 动作捕捉镜头。

引用格式 刘丽.基于 UWB/INS 的室内组合定位技术研究[D].哈尔滨工业大学，2021.DOI：10.27061/d.cnki.ghgdu.2021.001231.

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基于 HSI 的集群机器人室内搜索方法研究

关键词

人-集群交互；集群机器人；室内搜索；虚拟现实；眼动控制

摘要

面向地震坍塌、火灾救援等复杂搜索场景，发展机器人技术代替人工进行目标搜 索，不仅可以减少不必要的人员伤亡，还能提高任务执行的效率。相比于单体机器人， 集群机器人具有高鲁棒性、可扩展性及并行协同作业等优点，可以显著扩大搜索任务 的覆盖范围，增强容错性。然而，其数量众多、群体感知困难、集体行为指控不易， 在复杂度高、障碍物多的未知室内环境执行搜索任务时，智能化程度难以满足任务需 求。针对上述问题，本文基于人-集群交互技术（Human-Swarm Interaction，HSI）开 展集群机器人的室内搜索方法研究，实现操作者与集群机器人协作完成未知环境目标 搜索任务。本文的主要工作如下：（1）针对非结构化空间中资源受限、不确定性强的目标搜索问题，提出一种虚实结合、人机混合智能的 HSI 系统。论述室内复杂搜索现场的未知多目标搜索任务特征，分析 HSI 系统虚实环境信息实时更新、搜索控制指令灵活交互等功能需求。明确系统中操作者、集群机器人执行搜索任务时的角色定位，制定无线通信、互联互通的 闭环 HSI 系统总体方案。（2）面向远距离、广覆盖及限制搜索人员直接参与的复杂搜索现场，提出一种 基于 VR（Virtual Reality）的远程搜索现场可视化方法。结合虚拟现实技术，构建数字孪生 3D 搜索场景。在所搭建的可视化环境中，开发多视角窗口全景呈现搜索现场信息，增加机器人运动轨迹等可视化元素优化交互界面，实现操作者对集群机器人作业现状的沉浸式遥感知，方便操作者根据现场情况灵活输出搜索意图。（3）针对集群机器人自主搜索智能化程度有限、操作者先验知识和智能决策难以充分发挥的问题，提出一种基于眼动的 HSI 协同搜索方法。结合眼动控制技术，采集和预处理操作者眼动数据生成集群运动控制指令，遥控制集群机器人分组并行作业 和动态调整搜索路径，规避不相关搜索区域、自主精细化覆盖相关搜索子区域，合理分配人机资源，充分发挥人机智能各自优势。（4）开展面向未知室内环境的 HSI 协同搜索实验验证。搭建包含仿真实验系统 和集群机器人实物实验系统的集群搜索实验平台，全流程开展基于 HSI 的集群机器人室内搜索方法实验验证，分析虚拟和真实搜索环境中集群搜索轨迹、个体运动朝向 及操作者眼动瞳孔位置等实验数据。实验结果进一步验证了本文所提方法的可行性，该方法在有效提高集群机器人搜索效率及被控精度的同时，减轻了搜索人员的工作强度，为搜索工作的实施提供了一种新的途径。

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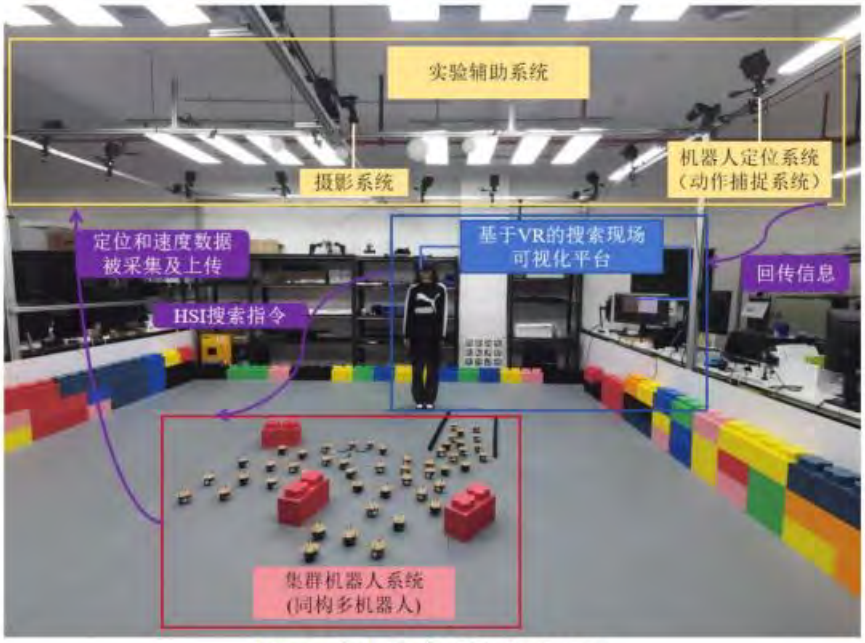

图 5.3 HSI 搜索系统实验环境

NOKOV 度量动作捕捉在研究中的应用摘录

完整的光学动作捕捉系统由红外光学镜头、动作捕捉软件、反光标志球、POE 交换机、线缆、标定杆以及三脚架等镜头固定装置组成。本系统采用 NOKOV 运动捕捉系统，搭载了 16 台 Mars 品牌的动作捕捉相机，实现机器人亚毫米级定位，捕捉机器人运动信息。将相机采集到的机器人位姿信息通过交换机回传至虚拟现实交互环境中，从而更新机器人的运动状态。此外，实验场地的上空安装有一台型号为 Basler a2A4504-18ucPRO 的高清摄像机，其视角自上而下，全程监控并记录实验过程，准确展现机器人的动态行为和运动轨迹。

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基于 RFS 空概率的多移动传感器避碰与围捕方法研究

关键词

标签随机有限集空概率；多传感器资源配置与管理；避碰避障；环航围捕；多目标跟踪

摘要

多目标跟踪领域中多传感器系统由于其信息来源丰富、观测区域广、适应性强等优势得到了大量的研究。在多目标跟踪过程中,多传感器系统资源配置与管理可分为多传感器分配与调度、多传感器控制、多传感器避碰以及多传感器围捕等方面。标签随机有限集(Labeled Random Finite Set,L-RFS)空概率泛函是一种有效的随机有限集(RFS)统计描述方法,与多目标概率密度函数、概率生成泛函和置信质量函数等描述方法相比,具有直观描述 RFS 中随机集值点的分布特点。目前面向多目标跟踪的多传感器资源配置与管理仍然有较多的问题未被解决,例如在部分重叠视场中多目标的有效跟踪、在多传感器分配与调度中的控制与避碰、目标被多传感器编队包围之后出现逃逸等。针对上述问题,本论文利用 L-RFS 空概率泛函对多传感器资源配置与管理中的多目标跟踪、多传感器分配与调度、避障与环航围捕问题进行研究,主要研究工作包括以下三个方面:(1)部分重叠视场的多传感器多目标跟踪算法研究。针对部分重叠视场中的多目标跟踪问题,本论文研究了传感器检测概率场模型以及量测驱动的多目标出生模型,并由此给出了部分重叠视场的多传感器广义标签多伯努利(Generalized Labeled Multi-Bernoulli,GLMB)滤波器。仿真结果表明,该算法可以有效地跟踪视场存在重叠的场景,并且有着较好的目标跟踪能力和较高的精度。(2)基于 L-RFS 空概率的多移动传感器控制与避碰算法研究。针对现有的多传感器控制方法较少考虑传感器与目标之间或传感器相互之间的控制和避碰问题。论文首先提出了一种综合性的多传感器控制代价函数,其包括 Kullback-Leibler(K-L)散度、检测概率和传感器使用成本。其次,为了解决上述的避碰问题,给出了一种基于 L-RFS 空概率的避碰策略。该策略本质上是在传感器或目标周围建立一个安全区域,然后将安全区域中的空概率取值和多传感器控制代价函数结合起来作为整体的评价函数。仿真与实验证明了该多传感器控制和避碰算法的有效性。(3)基于 L-RFS 空概率的多移动传感器避碰、避障与环航围捕算法研究。针对目标被多传感器编队包围之后可能出现的逃逸问题,本论文提出了一种基于 L-RFS 空概率的多移动传感器环航围捕控制策略,该策略中所有传感器分布式协作参与围捕,其容错性高且适应性强,有着较为广阔的实用价值。同时本论文给出了围捕过程中编队生成与编队保持两个阶段的传感器避碰策略,其能够有效避免多传感器系统在围捕过程中的碰撞风险。仿真与实验表明,本论文所提出的围捕控制策略具有较高的成功率,其实时性好,扩展性强。同时多传感器避碰策略面对障碍物时能够规划出平滑的轨迹,可以保证传感器与目标,传感器与障碍物,以及其余传感器之间有一定的安全距离。综上,本论文研究了多传感器资源配置与管理中的分配与调度、避碰与避障以及编队与围捕问题,利用基于 L-RFS 空概率泛函的方法给出了解决上述问题的新方法。仿真与实验表明了本论文所提方法的有效性和可行性。

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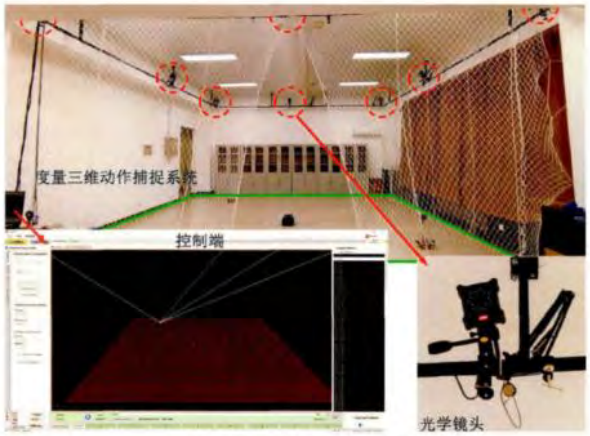

图 6-1 度量光学三维动作捕捉系统

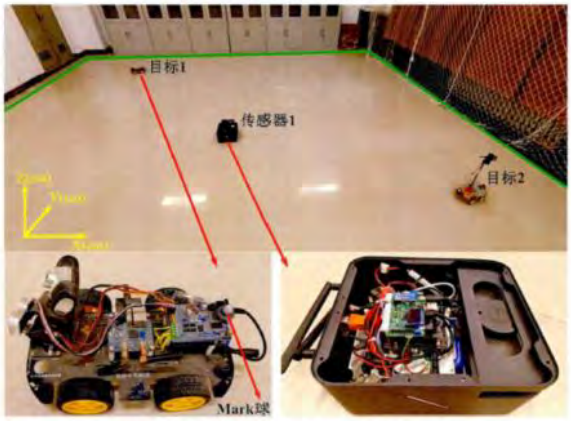

图 6-2 初始场景，全向麦轮小车(右)与智能小车(左)

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> *在实验场景中，传感器以及目标的真实位置和速度由 NOKOV（度量）光学三维动作捕捉系统提供。该动捕系统由 8 个高性能红外摄像头等距分布在正方形场地上空，红外摄像头最大观测距离 40m,像素 1200 万，帧率 300-600Hz,延迟 3rns。动捕系统可提供的位置精度为 0.01mm,采样时间设置为 0.03s。*

引用格式 刘启亮. 基于 RFS 空概率的多移动传感器避碰与围捕方法研究[D].陕西科技大学,2023.DOI:10.27290/d.cnki.gxbqc.2023.000410.

链接

https://kns.cnki.net/kcms2/article/abstract?v=lxlxReJOxldCWgaxBxvqrY9fxL9pchsa19_0Fq1NZiBuyxRbAWbut-yfBD9gwVPMeIM6gPdmozsmsPT97RyNfvBui7LeFNYehSDpyKdlUy89CNDQqTuqEA==&uniplatform=NZKPT&language=gb

基于 ROS 的无人车多源融合导航方法

关键词

多传感器融合；组合导航；卡尔曼滤波；故障检测

摘要

随着无人车(Unmanned Ground Vehicle,UGV)在军事、运输、仓储管理等不同领域中的广泛运用,对于无人车导航定位技术的需求也日益增加。在空旷的室外环境中,可以通过全球卫星导航系统(Global Navigation Satellite System,GNSS)进行精确的定位服务,但在有些应用场景当中难以获取卫星信号,此时需要其他技术完成无人车准确可靠的导航定位服务。由于各导航传感器各有其局限性,多传感器融合定位方法是今后研究的重点之一,多源融合定位的核心是充分利用可用导航信息得到全局最优的定位结果,针对此问题本课题进行了以下内容的研究:首先本文选取航姿参考系统、激光雷达里程计、轮式里程计及超宽带定位系统作为本文的导航传感器,使用航姿参考系统中的惯性导航信息作为参考导航信息,使用卡尔曼滤波器将惯性导航信息与其他辅助导航传感器信息进行融合。为了解决不确定量测噪声对估计结果的影响,本课题采用了一种基于变分贝叶斯估计的自适应卡尔曼滤波器估计量测噪声协方差矩阵,提高了导航系统的鲁棒性；为了实现融合算法的即插即用性与实时性,本课题采用了广义序贯滤波算法,降低了计算复杂度同时加强了融合算法的可扩展能力；为了解决导航传感器失效情况的影响,本课题采用了一种基于残差χ2 检验/改进自主完好性检测外推法的联合故障检测方法,能够利用历史新息序列判别并隔离故障导航信息,并在广义序贯滤波框架当中利用无故障导航信息进行重构。最后本课题在对上述所提出的方法进行仿真验证的基础上,搭建了多传感器无人车试验平台,并在试验平台上利用 ROS 系统编写了多源导航算法包,使用动作捕捉系统进行室内试验以验证算法性能。试验结果表明,该多源融合导航方法能够有效提高导航系统的鲁棒性、容错性与定位精度。

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本课题试验无人车的真实位姿使用动作捕捉系统（Nokov）获取，动作捕捉系统通过布置的十六个动作捕捉相机捕捉在无人车上建立的刚体模型，能够获取无人车相对于动作捕捉房间的精确六自由度位姿数据。通过在车上安装的反光标记点，便可以使用动作捕捉软件建立无人车刚体模型。

引用格式 王浩. 基于 ROS 的无人车多源融合导航方法[D]. 哈尔滨工业大学,2022.DOI:10.27061/d.cnki.ghgdu.2022.004408.

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https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C475KOm_zrgu4sq25HxUBNNTmIbFx6y0bOQ0cH_CuEtpsKfbYn5YM1XXP5RqiGxGm_JgaSa38h6xhbLOghskpmrz&uniplatform=NZKPT

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基于 UWB 的煤矿井下数字孪生定位关键技术研究

关键词

智慧矿山；数字孪生；目标定位；扩展粒子滤波

摘要

煤矿井下目标位置信息是实现智慧矿山的重要支撑保障。受条件限制，井下定位算法的评估大都基于仿真环境，未能充分考虑实际巷道环境及定位基站部署等因素对定位精度的影响。此外，由于井下环境复杂恶劣，在地面效果良好的定位技术无法直接应用到井下。针对上述问题，本文设计了煤矿井下数字孪生定位系统框架，为定位算法评估提供矿井孪生环境，并且基于超宽带（Ultra Wide Band， UWB）/惯性量测单元（Inertial Measurement Unit，IMU）提出改进定位算法，以提升井下目标定位性能。主要研究内容如下：

（1）针对井下定位算法难以实地评估，而基于高斯噪声假设的仿真实验又不能保证评估结果真实性的问题，提出一种煤矿井下数字孪生定位系统框架。该框架包括物理空间、数字空间、孪生服务、孪生数据和连接五部分，可以实现井下环境、测距信息的实时获取，并为用户提供孪生环境定制、孪生定位实验等服务。为了在孪生环境下还原 UWB 基站实际测距误差，在数字空间中提出测距行为模型，有效刻画了遮挡物和距离对测距精度的影响。

（2）针对扩展粒子滤波（Extended Particle Filter，EPF）算法存在粒子分布不合理和粒子贫化的问题，首先提出基于目标加速度的 AF-EPF 算法，利用粒子三轴加速度概率，结合权重偏移参数对粒子状态进行偏移，提高粒子多样性。进一步，研究基于巷道拓扑约束和目标运动约束的粒子筛选优化策略，利用巷道结构特点以及 IMU 获取的加速度信息对粒子进行约束，提出 AF-TP-EPF 算法。通过实验验证了上述算法相比 EPF 的优越性。

（3）在上述研究的基础上，开发了煤矿井下数字孪生定位系统，实现了孪生漫游、孪生环境定制和孪生定位实验等功能。针对煤矿井下复杂环境和实际孪生服务需求，基于 Vue 生命周期和 Promise 机制完成变量优化和模型分层同步加载，采用 WebSocket 和 JSON 进行实时通信和算法调用，借助键鼠监听事件实现孪生体拾取、目标操控和碰撞检测，提高了系统性能和用户体验。该论文有图 47 幅，表 9 个，引用格式 85 篇。

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图 4-9 实验场景及设备部署

Figure 4-9 Experimental scene and device setup

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无人机参考位置的获取使用 NOKOV 三维动作捕捉系统，将八个动捕相机排列成矩形，以微小的定位误差获取无人机的三维坐标，作为参考位置。

引用格式 贾丁.基于 UWB 的煤矿井下数字孪生定位关键技术研究[D].中国矿业大学，2023.DOI：10.27623/d.cnki.gzkyu.2023.001448.

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https://kns.cnki.net/kcms2/article/abstract?v=DFdco8SIy0I0aK39Viz97fvCuHYplOSaNOU_Dx4YsIhMfd3zw2Q2TjCLvlOPLoYnXjsCBBt9qbadw4wVvGIIZLzTeZLaEq8qbucZcVIcWN4G_bPEH5NYRQ==&uniplatform=NZKPT&language=gb

基于 UWB 相对测距的协同定位系统设计

关键词

多机器人系统;非线性状态估计;协同定位;超宽带;拓展卡尔曼滤波;可观性分析;误差状态变换;

摘要

针对多机器人系统在外部导航设备不可用或弱通讯的环境下集群协同自主导航问题，开展了基于超宽带（UWB）相对量测的多机器人一致性协同定位问题的研究。首先，建立了多机器人协同定位问题的状态模型以及 UWB 相对量测模型，并且推导了线性化误差状态系统。其次，分析了标准拓展卡尔曼滤波（EKF）在协同定位中不一致的原因，揭示其本质源于原始非线性系统与估计器的线性化误差状态系统之间可观性不匹配。再次，提出了一种基于线性时变变换的估计方法，进而设计了 KD-EKF 估计算法避免了可观性不匹配问题。然后，进行了蒙特卡洛仿真测试实验，证明 KDEKF 相较于标准 EKF 以及 FEJ-EKF 方法具有更高的定位精度以及更好的一致性。最后，开发了基于 Tucker 地面机器人的多机器人系统实验平台，对设计的 KD-EKF 估计算法进行了实验验证，证明了提出算法的有效性，KD-EKF 在位置误差上较标准 EKF 下降约 6.74%，在方位误差上下降了约 37.03%。

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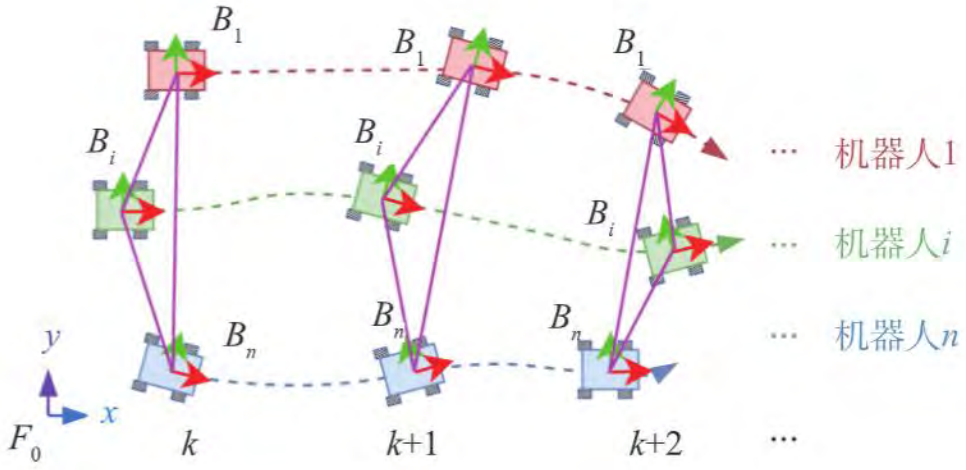

图 1　协同定位系统的示例场景

NOKOV 度量动作捕捉在研究中的应用摘录

5 实物实验
为验证所提出系统的可行性，本文搭建了一个由三个二轮差动驱动机器人组成的协同定位系统，平台详细配置如图 6 所示。具体来说，本文使用 TARKBoL-R20 作为机器人平台，每个机器人配备树莓派 5 作为嵌入式计算机。每台机器人都配置有一个 STM32，主要负责获得从编码器获取轮速，并配备两个 Nooploop UWB 模块获取绝对距离量测，其在机体坐标系下的位置为\[0 0.15]和=\[0 -0.15]。为评估定位性能，本文使用 Nokov 运动捕捉系统跟踪机器人位置和方向，作为真值。

引用格式 张欣瑶,郝宁,贺风华,等.基于 UWB 相对测距的协同定位系统设计[J].无人系统技术,2025,8(04):78-88.DOI:10.19942/j.issn.2096-5915.2025.04.37.

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基于安全强化学习的多智能体覆盖路径规划

关键词

多智能体系统； 覆盖路径规划； 安全强化学习； 值分解网络

摘要

覆盖路径规划的目的是为智能体找到一条安全的轨迹，其不仅可以有效覆盖任务区域，而且 可以避开障碍物与邻近智能体。 在执行覆盖任务时，复杂的大面积任务区域总是不可避免的。 如何在保 证智能体安全的前提下加强智能体之间的协同合作，以改善集群任务效率低、能力不足的缺点是值得探 索的问题。 为此，利用栅格地图建立离散的覆盖路径规划数学模型，提出一种基于值分解网络的安全多 智能体强化学习算法，并通过理论证明论证其合理性。 该算法通过分解群体价值函数以避免智能体的虚 假奖励，有助于加强智能体之间协同覆盖策略的学习，以提高算法的收敛速度。 通过在训练过程中引入 屏蔽器以修正智能体的出界和碰撞等行为，保证智能体在整个任务过程中的安全。 仿真和半实物实验结 果表明，新算法不仅可以保证智能体的覆盖效率，同时还能有效维护智能体的安全。

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图 15　半实物仿真示意图

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半实物平台由动作捕捉系统和无人车组成。动作捕捉系统使用北京度量科技有限公司生产的ＮＯＫＯＶ（度量）光学三维动作捕捉系统,用于无人车定位。

引用格式 李松,麻壮壮,张蕴霖,等.基于安全强化学习的多智能体覆盖路径规划[J].兵工学报, 2023, 44(S02):101-113.DOI:10.12382/bgxb.2023.0881.

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http://www.co-journal.com/CN/10.12382/bgxb.2023.0881

基于电磁环境感知的无人机集群航迹规划问题研究

关键词

无人机集群，航迹规划，电磁环境感知，生成对抗网络，多智能体强化学习

摘要

作为无人机集群自主飞行的关键技术，航迹规划旨在规划一条由起始点到目标点的安全航迹。随着无人机集群所处电磁环境日益复杂，无人机集群的航迹规划既要避免碰撞，也要避开强电磁干扰区域。然而，由于在未知环境下，全局电磁环境信息难以提前获取，基于电磁环境地图已知的航迹规划算法难以适用。为适应未知的电磁环境，如何设计由局部观测推断全局信息的电磁环境感知方法，并基于感知结果进行航迹规划控制，是成功实现未知电磁环境下无人机集群自主导航的关键。因此，本文研究未知电磁环境下的无人机集群航迹规划问题，分别考虑电磁环境感知和航迹规划控制两个方面，其主要的研究工作叙述如下：

1、现有构建电磁环境地图的方法大多适用于均匀采样导致的数据缺损，应用场景有限。因此，本文进一步考虑了更为一般的数据缺损情况：因限制区域（禁飞区等）的存在而造成的整体数据缺损（块缺损），并设计了一种基于弱监督学习的生成对抗网络算法用于电磁地图构建。为提高构建精度，采用了 U 型马尔可夫判别器，并结合 U-Net 和残差网络设计了生成器。仿真实验表明，相对于现有方法，本文算法在两种缺损数据下的构建结果的均方根误差分别降低了 0.526 和 2.024，提高了单机感知环境的范围和精度。

2、为了使无人机集群在巡航过程中避开强电磁干扰区域，且保证机间避撞，本文提出了基于电磁环境感知的多智能体深度策略梯度算法，利用多智能体强化学习来求解集群的最优航迹。一方面，将本文提出的电磁环境感知方法加入到模型训练中，通过周期性构建电磁地图并作为模型输入来辅助智能体规划航迹，从而提高学习效率；另一方面将无人机集群内部避碰作为安全约束，并基于控制障碍函数设计了对应的防护机制来修正不安全策略。相比于传统的无模型强化学习方法，本文方法通过智能体对环境的感知加快了算法的收敛，且能以较优路径实现航迹规划，同时避免个体试错学习过程中违反安全约束，保障了集群在未知环境下的安全性。最后通过仿真实验验证了算法的性能。

3、本文搭建了由四旋翼无人机、光学动作捕捉系统和通用软件无线电外设组成的半实物仿真平台，以定向天线发射通用软件无线电外设所调制的信号分布作为电磁环境地图，通过半实物实验验证了算法的有效性。

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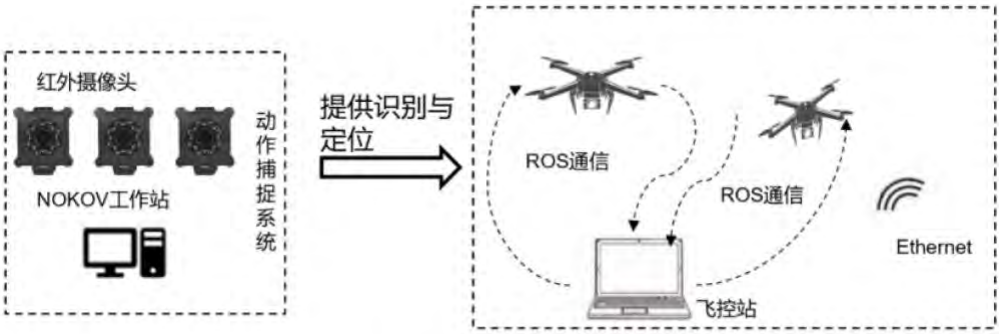

图 5-3 平台整体结构

NOKOV 度量动作捕捉在研究中的应用摘录

本文实验平台的动捕系统是由 NOKOV 所生产的光学动作捕捉系统，主要配件为 NOKOV 的 Mars4H 光学动捕摄像头、POE 交换机和提供的主机工作站。

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https://kns.cnki.net/kcms2/article/abstract?v=DFdco8Sly0KysSmYGPdmWDBWYg5H6XlXXDlrIK3z9F09_c6E4iAFauNn0yFBustgn4sVkN7z8aVjzeTbxBUAoIotEeMLb1fKEm_QS5bR8Z6xaSg6zf-iyA==&uniplatform=NZKPT&language=gb

基于多智能体强化学习的灾后多无人机协同轨迹优化方法研究

关键词

无人机轨迹优化，灾后通信网络覆盖，目标搜索，多智能体深度强化学习，注意力机制

摘要

无人机因其灵活和易部署的特点，在灾后应急救援任务中已经得到了广泛应用，如 利用无人机执行应急通信网络覆盖和目标搜索任务。在灾后救援任务中，部署由多个无 人机组成的集群，相较于单个无人机，可以显著提升系统的感知能力、任务执行效率、 鲁棒性以及扩展性。尽管多无人机系统具有以上诸多优点，但其控制难度也显著增加， 仍存在许多待解决的问题。对于灾后多无人机应急网络覆盖任务，需要解决在保证连通 性的同时优化通信效率的问题；对于灾后多无人机协同目标搜救任务，需要解决集群规 模提升以及搜索效率优化的问题。 针对上述问题，本文围绕着灾后多无人机协同轨迹优化方法展开研究，主要的研究 工作如下： （1）针对灾后多无人机应急网络覆盖任务中，如何在满足连通性约束下实现动态 网络覆盖和通信效率最优的问题，提出了一种基于多智能体深度强化学习和自注意力网 络的多无人机协同轨迹优化算法（Double-Stream Attention multi-agent Actor-Critic， DSAAC）。该算法以最大化通信效率为优化目标，并综合考虑无人机的吞吐量、安全距 离、耗电量等因素设计了奖励函数。通过双数据流的网络结构，使 Actor 网络能够处理 状态信息的变化量，提高了无人机对动态信息的感知能力。在 Critic 网络中加入了 Transformer 编码器，通过注意力机制聚合相关协作无人机的信息，使多无人机间建立有 效的合作策略，并解决了无人机和用户数量增多时带来的模型维度灾难问题。仿真结果 表明，DSAAC 算法在通信效率、吞吐量以及避障性能均优于对比算法。 （2）针对灾后多无人机目标搜救任务中，如何实现无人机远距离通信、集群规模提 升以及目标搜索效率优化等问题，本文提出了一种基于多智能体强化学习和图注意力网 络的异构多无人机协同轨迹优化算法（Graph Attention Network multi-agent Actor-Critic， GATAC）。在该算法中，采用了一种领航者-跟随者的多无人机协作策略，固定翼无人机 充当领航者提供中继通信网络覆盖，多旋翼无人机充当跟随者进行低空多目标搜索，实 现了无人机远距离通信和目标搜索。通过构建一种协作关系图，并引入图注意力网络模 型来聚合相邻节点信息，从而提升了无人机的协作规模。另外，提出了一种多无人机状 态观测优化方法，通过协作重要性指数和搜索目标重要性指数来精简状态观测向量，提高了多目标搜索时的协作效率。仿真结果表明，GATAC 算法在探明目标数量和能耗表 现均优于对比算法。 （3）为了对多无人机轨迹优化算法进行实机验证，本文构建了一个基于动作捕捉 定位系统的多无人机协同验证平台。首先，基于动作捕捉技术搭建了一个室内定位系统， 实现多无人机亚毫米精度的定位。其次，基于 Crazyflie 和 Crazyswarm 平台构建了一个 室内多无人机协同飞行控制系统，实现多无人机轨迹闭环控制。

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最后，将前文提出的算 法部署至该实物平台，并完成相关实验设计和结果分析。实验结果表明，本文提出的算 法迁移至实机环境依然能够稳定运行，并能够完成通信网络覆盖和目标搜索任务。综上所述，本文针对灾后通信网络覆盖和目标搜索任务中，多无人机协同轨迹优化 方法进行了研究。仿真实验和实物实验表明，所提出的算法与对比算法相比，性能均有 明显提升。相关研究对无人机应用于灾后救援任务中有着积极的理论和实践意义。

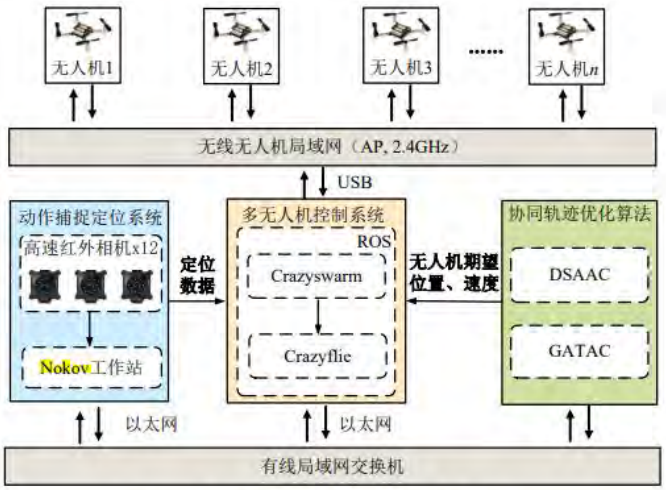

图 5-1 多无人机协同实机验证平台架构

NOKOV 度量动作捕捉在研究中的应用摘录

动捕定位系统采用 Nokov 度量公司的国产方案，其基本原理是通过多个摄像头同时拍摄反光小球，经过上位机软件进行位置解算实现亚毫米级别的三维空间定位。该系统可以将无人机的位置速度等信息打包成机器人系统（Robot Operating System，ROS）消息包，通过以太网交换机与其他子系统进行无人机实时信息反馈。其中，ROS 系统是一个用于机器人应用开发的开源操作系统，它提供了包括硬件抽象、底层设备控制、常用功能实现、进程间消息传递以及包管理等类似传统操作系统的功能。ROS 的设计目标是提高机器人软件开发的代码复用率，它采用分布式处理框架，允许可执行文件在运行时松散耦合，从而提高了系统的灵活性和可扩展性。因此，本文的多无人机实机验证平台均基于 ROS 系统实现子系统间通信。

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https://kns.cnki.net/kcms2/article/abstract?v=6h6U53PWxNTSQwXZpS6bTpIgoxggD2Ut8--Y9JmtKb9zcMgCXyt028BkOBMBAVtnemenwwc6dBPD_jzPzTB14xHXFxKsDOWbK9IF19SW8s8Erv8ZWpJFltRg16p_mN3PlnG-D4KWCgMNA2NTPTv2rEf4z21ZdmE3CQWrzs2d4_SkINJB84wIaW6Mnvz6m0ri&uniplatform=NZKP

基于改进值迭代的无人机持续监测路径规划

关键词

无人机；持续监测；路径规划；值函数迭代；轮盘选择

摘要

无人机持续监测路径规划问题是当下的一个研究热点。现有的无人机硬件和智能优化算法的飞速进步，使得单体无人机的智能化程度大大提高，实现了从单机智能到多机协同智能的跨越式发展。针对监测路径信息安全问题，本文研究了单无人机和多无人机在时间和安全性约束下的持续监测路径规划问题。

首先，本文针对现有算法的建模方式进行了改进。为了提高持续监测任务的时效性和安全性，本文提出了一种新的适用于无人机路径规划的值函数迭代方法。传统值函数迭代算法将奖励收益函数与动作相关联，没有考虑到待监测目标点的时效性，但实际应用中要求目标点需要在最大允许监测周期内被无人机访问，本文运用ε原则提高了路径点选择的随机性，并用监测路径的信息熵对随机性进行评估，最后得到了监测路径安全性好的持续监测路径。

其次，针对多无人机持续监测问题，本文建立了多无人机持续监测路径规划模型。为保证无人机状态的同步更新，运用离散化预处理的方法，将路网分成多份相同长度的线段；为提高持续监测路径的随机性，运用轮盘赌方法对拓展的虚拟节点进行随机选择，在非完备的路网环境中验证了算法的可行性。

最后，运用实物实验平台对设计的算法进行验证，结果显示无人机飞行路径与仿真实验路径的偏差较小，得到了很好的实验效果。仿真实验和实物实验结果共同验证了本文所提出方法可以有效提高无人机持续监测的效率和安全性。

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图 5.2 实物实验场景

NOKOV 度量动作捕捉在研究中的应用摘录

本章详细介绍了实物实验平台—NOKOV 动作捕捉系统，它配备了精度较高的 Mars 系列相机，能在多个领域发挥重要作用，如构建虚拟游戏人物、辅助室内无人机和无人车的定位与导航，辅助他人完成康复训练等。本章运用该动作捕捉系统完成了单无人机持续监测路径规划的实物实验，验证了设计算法的有效性。

引用格式 刘晨.基于改进值迭代的无人机持续监测路径规划[D].武汉科技大学，2023.DOI：10.27380/d.cnki.gwkju.2023.000649.

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基于概率推理的无人机同时轨迹估计与规划方法研究

关键词

轨迹估计；轨迹规划；概率推理；高斯过程；因子图

摘要

作为自主无人系统之一，无人机由于其用途灵活，对各类场景适应能力强的特点，在探测、巡视以及救援等任务中有广泛的应用空间。在很多情况下，无人机需要在未知、动态变化且障碍密布的复杂环境中完全自主地工作，再加上无人机机载资源的限制，对其状态估计和运动规划能力提出了巨大的挑战。传统框架中，状态估计和运动规划依照串行方式进行工作，这一方面引入了额外的数据传输和存储消耗，另一方面很难实现两模块间不确定性的有效传递和处理。

针对这一问题，本文从系统角度考虑无人机算法框架的集成轻量化，研究一种基于概率推理的同时轨迹估计与规划算法，将状态估计与运动规划统一在概率推理的理论框架下进行建模和求解，使两者合二为一，相互促进。

首先研究了基于高斯过程的连续轨迹估计方法。将无人机轨迹估计问题描述为一个最大后验估计问题，并通过最小二乘优化进行求解。在建模过程中，引入基于高斯过程的连续时间轨迹表示，并用因子图模型进行表述，进一步利用矩阵稀疏性和因子图优化的增量特性，提高求解效率。

然后研究了基于概率推理的连续轨迹规划方法。将无人机轨迹规划视为一个概率推理问题，依然采用基于高斯过程的连续时间轨迹表示，将障碍物躲避等约束描述为一系列二值事件，通过求解其对应的最大后验估计问题，找到使无人机安全达到目标点概率最高的轨迹。在此基础之上，将该方法进一步扩展到多无人机编队轨迹规划的场景，分别进行了仿真和实物实验，验证了可行性。

最后，将以上两部分融合为一个整体，研究了基于概率推理的同时轨迹估计与规划方法。将两者统一在概率推理的理论框架下，描述为一个完整的最大后验估计问题，并使用一个统一的因子图模型进行表示和求解，从而同时得到轨迹估计与轨迹规划的结果，通过仿真测试证明了其可行性。

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图 4-13 实验所使用的 Crazyflie 小型无人机和 NOKOV 运动捕捉系统

NOKOV 度量动作捕捉在研究中的应用摘录

由于多无人机编队的任务场景是单无人机的扩展，具有更高的难度和复杂度，因此本节将直接给出多无人机编队任务场景的仿真和实物实验结果。为了分别测试前文中介绍的各类约束因子的有效性，分别设计了四个实验场景：双机避碰、队形保持、多机编队重规划、多机自适应队形变换。实验使用了 Crazyflie 小型无人机，同时用 NOKOV 运动捕捉系统对无人机进行定位，如 图 4-13 至图 4-14 所示。

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基于惯性导航和 UWB 定位的室内无人车导航技术研究

关键词

超宽带；惯性导航；卡尔曼滤波；组合定位

摘要

随着科技的发展，无人系统进入到了越来越多的领域当中，如自动驾驶汽车、无人快递投放小车、无人仓库管理系统等。在无人系统中，实现精确的定位和导航至关重要。在室外情况下，全球卫星导航系统(Global Navigation Satellite System,GNSS)的日益成熟可以提供精确的导航服务，而在室内情况下，由于很难获取卫星信号，难以发挥作用。随着人们对于室内定位导航的需求加大，出现了许多室内定位方案。但是单一的定位技术难以满足实际应用中的精度要求，固本文提出了一种基于惯性导航和超宽带（Ultra Wide Band，UWB）定位的室内无人车导航技术。

本文以无人小车为研究对象，主要研究室内环境中的导航定位算法。分析了基于到达信号强度、基于到达角度、基于到达时间、基于到达时间差四种 UWB 定位信息获取方法；讨论了单边测距算法和双边测距算法并使用双边双向测距算法对测距误差标定；对 UWB 定位误差来源进行了分析，并提出抑制天线误差、非视距误差、时钟误差、多径效应的方法。为了提高 UWB 的定位精度，本文提出了基于卡尔曼滤波的 UWB 定位算法，相较于最小二乘定位算法，定位效果有了明显的提高；为了解决在非视距环境中 UWB 测距信息会出现野值，影响定位精度的问题，本文研究了基于扩展卡尔曼滤波的 UWB/IMU 的组合定位算法；为了解决物体在运动过程中量测噪声协方差矩阵出现突变，影响扩展卡尔曼滤波算法定位估计的问题，本文提出了基于简化 Sage-Husa 自适应卡尔曼滤波的 UWB/IMU 组合定位算法。

最后对组合定位算法进行了仿真，并将本文中所建立的 UWB/IMU 组合定位系统在搭建的试验车载平台上进行了实物试验，实物试验的结果表明，本文提出的基于 UWB/IMU 的室内无人车导航算法有效的提高了定位精度。

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图 5-5 Mars 2H 高速摄像机

NOKOV 度量动作捕捉在研究中的应用摘录

光学式动作捕捉，顾名思义，是通过光学原理来完场物体的捕捉和定位的。是通过光学镜头捕捉固定在人体或是物体上面的 marker 的位置信息来完成动作姿态捕捉。光学动作捕捉可分为被动式和主动式两种。这个分类是从 marker 来区别的。主动式是指 marker 是主动发光甚至可以自带 ID 编码的，这样镜头在视野中可以通过 marker 自身发光来观测它，并记录捕捉到其的运动轨迹。而被动式光学动作捕捉是通过镜头本身自带的灯板发出特定波长的红外光，照射到 marker 上，marker 是通过特殊反光处理，可以反射镜头灯板发出的红外光，这样镜头就能在视野里捕捉记录该 marker 的运动轨迹。 本次试验的真值将使用 Nokov 公司生产的 Mars 系列中的 Mars 2H 光学式动作捕捉系统，下表为它的一些具体参数

引用格式 火元亨.基于惯性导航和 UWB 定位的室内无人车导航技术研究[D].哈尔滨工业大学，2021.DOI：10.27061/d.cnki.ghgdu.2021.002369.

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基于角度搜索和深度 Q 网络的移动机器人路径规划算法

关键词

移动机器人; 路径规划; 深度 Q 网络; 角度搜索策略; 物联网信息融合技术

摘要

针对深度 Q 网络（Deep Q Network,DQN）算法在求解路径规划问题时存在学习时间长、收敛速度慢的局限性,提出一种角度搜索（Angle Searching,AS）和 DQN 相结合的算法（Angle Searching-Deep Q Network,AS-DQN）,通过规划搜索域,控制移动机器人的搜索方向,减少栅格节点的遍历,提高路径规划的效率。为加强移动机器人之间的协作能力,提出一种物联网信息融合技术（Internet Information Fusion Technology,IIFT）模型,能够将多个分散的局部环境信息整合为全局信息,指导移动机器人规划路径。仿真实验结果表明:与标准 DQN 算法相比,AS-DQN 算法可以缩短移动机器人寻得到达目标点最优路径的时间,将 IIFT 模型与 AS-DQN 算法相结合路径规划效率更加显著。实体实验结果表明:AS-DQN 算法能够应用于 Turtlebot3 无人车,并成功找到起点至目标点的最优路径。

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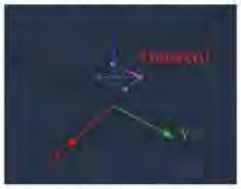
(a) 实验地图 (b) Turtlebot3无人车 (c) 高清镜头
(a) Experimental map (b) Turtlebot3 unmanned vehicle (c) HD lens

图 18 实体图片

Fig. 18 Physical images

(a) NOKOV动捕系统示意图
(a) NOKOV dynamic capture system



(b) 刚体示意图
(b) Rigid body

图 19 刚体和 NOKOV 动捕系统示意图

Fig. 19 Schematic diagram of rigid body and NOKOV dynamic capture system

NOKOV 度量动作捕捉在研究中的应用摘录

> *实体实验基于如图 1(a)所示的静态障碍物模将 NOKOV 度量动作捕捉系统连接镜头并标定坐标后,通过命令启动小车,整个系统调试完成后，将 Turtlebot3 无人车放在实验地图起点后,小车就能在神经网络的指导下运行,Turulebot3 无人车实际运行过程如图 20 所示。为了验证小车的运行轨迹是否和神经网络规划的路径相一致,通过 Rvz 建图在 Ubuntu 系统中显示 Turtlebot3 无人车的实际运行轨迹,如图 21 所示。*

引用格式 李宗刚,韩森,陈引娟,等.基于角度搜索和深度 Q 网络的移动机器人路径规划算法[J].兵工学报,2025,46(02):32-46.

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基于空地协同的翼伞无损回收地面移动平台控制研究

关键词

空地协同；航天器无损回收；无人车编队控制；轨迹跟踪控

摘要

随着航天技术的不断进步，人类获得了更多探索天空，宇宙的机会，但与 之相伴的是航天器成本的攀升。昂贵的成本使得许多公司和个人对航天领域望 而却步，阻碍了民用航天的发展。为了解决这一问题，航天器回收技术应运而 生。本文提出了一种利用地面移动网状回收平台实现对伞降航天器的无损回收 的方法。该技术将地面的无人车辆编队问题、翼伞轨迹追踪问题与无人车主自 动探测避障问题相结合，可以通过 ADRC（Active Disturbance Rejection Control ）控制算法控制地面多智能体编队的形状以及与无人车间的距离保持一致，同时 也通过人工势场技术实现了无人车编队自主避障的效果。这种方法将有望降低 航天器的发射成本，推动民用航天的发展。本文的具体研究内容如下： （1）搭建了由两辆无人车组成的包含协同控制系统的硬件平台。其硬件结 构由控制单元、通信系统、定位系统、信号装置等组成，其中，控制系统使用 的是控制系统使用的是能搭载多种外设的 STM32F103ZE 型号的嵌入式开发板、 定位系统使用的是 GPS（Global Positioning System）模块，信号装置采用 WiFi， 数传模块。能够实现定位，协同任务执行，避障等功能。 （2）在硬件平台的基础上，设计了基于无人车系统的软件控制平台。本文 利用 LabView 软件根据无人车硬件系统开发了无人车的控制系统，该系统通过 数传模块或 WiFi 模块实现数据和指令的传输。设计自主避障及跟踪模式以及手 动控制模式，以满足不同的应用场景需求，确保无人车能够准确执行控制指令。 这一软件控制平台与硬件平台紧密结合，共同实现了无人车的智能控制功能。 （3）将实际翼伞飞行数据作为领航者在软件中进行模拟仿真。为了提高仿真 结果的可靠性，分别对实际的翼伞以及无人车系统进行了数学模型的设计。将 验证后的模型加入到仿真环境中，通过采用不同控制算法来控制地面编队模型对翼伞模型的跟踪，并且将仿真结果进行比较获得不同算法下的编队跟踪性能， 证实 ADRC 算法在在抑制扰动、提高跟踪精度方面相比其他算法更有优势。此 外设计完成无人车真实相互跟踪实验，实验表明基于软件控制平台的双车协同 系统硬件平台能够执行跟随指令，保证两车之间能够保持稳定距离进行移动。

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图 1.14　无人机-无人车编队协同系统

NOKOV 度量动作捕捉在研究中的应用摘录

北京理工大学基于 NOKOV（度量）光学动作捕捉系统，成功构建了一个地空协同实验平台，该平台以无人机和地面无人车作为控制对象，能够验证多种异构智能体的控制算法，并模拟实现空地协同巡逻、无人车围捕以及探测围捕等多种军事应用场景。图 1.14 为北京理工大学所搭建的无人机-无人车编队协同系统。

引用格式　方文.基于空地协同的翼伞无损回收地面移动平台控制研究[D].南开大学,2024.DOI:10.27254/d.cnki.gnkau.2024.000063.

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基于密度交互的集群机器人自组织垃圾收集算法

关键词

集群机器人；集群清洁；密度驱动交互；垃圾收集；收缩机制

摘要

针对实际垃圾收集任务中垃圾常呈非均匀的斑块状分布的问题，提出一种基于密度交互的集群机器人自组织垃圾收集算法。首先，基于高斯核函数建立机器人邻域作业空间中垃圾分布及邻居分布的空间密度场；然后，在密度信息驱动交互规则作用下，集群机器人通过边缘包围行为实现对垃圾斑块的环型包围；最后，配合面向粗粒度垃圾的平推收缩策略和面向细粒度垃圾的涡旋收缩策略，以群体协作的方式推动垃圾斑块向内聚拢，完成斑块状垃圾的收集任务。数值仿真及真实集群机器人实验表明，所提收集算法对单斑块、多斑块及垃圾数量动态变化斑块中均具有良好的收集效果，表现出优良的并行作业和自适应性能。

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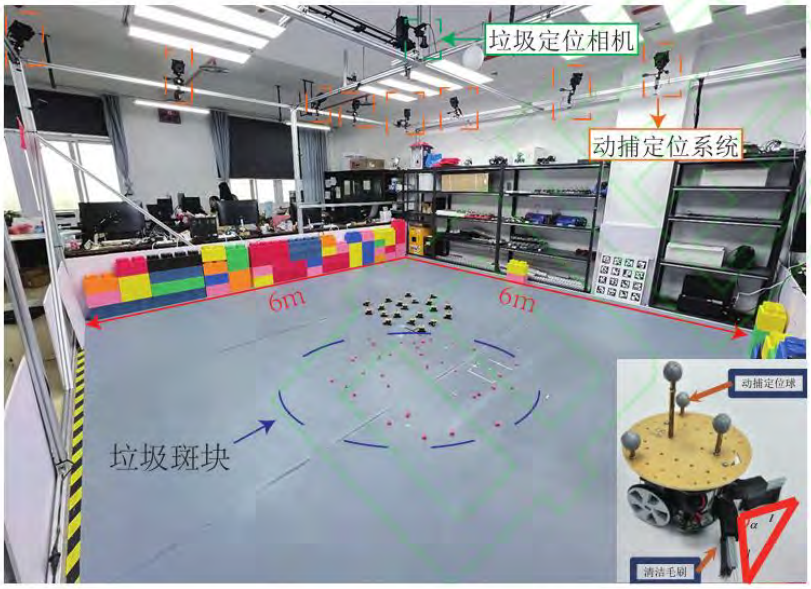

图 8　集群机器人与集群实验平台

NOKOV 度量动作捕捉在研究中的应用摘录

图 8 为实际集群机器人清洁实验的场地。该场地面积约 30m²，垃圾为不同大小的不规则红色泡沫块。集群机器人的位置、速度通过 NOKOV 动捕系统实时采集，垃圾的位置和数量通过场地正上方的垃圾定位相机采集。这些信息通过一台服务器运行算法后，生成各机器人下一时刻的期望角速度与线速度，通过定制通讯协议发送给各个机器人执行。

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基于神经回路策略的移动机器人导航算法研究

关键词

移动机器人，路径规划，人群导航，神经回路策略，深度强化学习

摘要

移动机器人安全高效地导航对于提升社会生活和工作效率具有重要意义，但是在人 群场景下，人群行为的多变性使得精确建模困难，机器人难以完全观测环境状态，因此 引发了专门研究人群导航的需求。尽管近些年来基于强化学习的方法已经取得了很大的 进展，但仍然存在一些挑战。首先，机器人在人群中导航不仅需要安全性，还需与人类 友好互动，维护人类接受度和舒适感。另一方面，密集和动态场景下，智能体交互复杂 不确定，导致导航准确性和安全性受限，静态异形障碍也是挑战之一，需要进一步研究 处理方法，以提高机器人导航性能。神经回路策略（Neural Circuit Policies, NCP）受线 虫神经回路启发，具有紧凑的网络结构与较强的鲁棒性，为解决上述挑战，本文将神经 回路策略应用到机器人导航中，研究了人群场景下机器人导航方法，主要研究内容如下： （1）针对移动机器人在导航中兼顾人群舒适感的问题，提出了一种融合生物神经 策略与注意力机制（Attention-Based Neural Circuit Policies, ANCP）的强化学习算法。该 算法采用强化学习框架，将 NCP 与注意力机制相结合，实现机器人导航的时空推理，捕捉人机交互的时空相关性，从而提高机器人在动态人群中的导航性能。在提高人群舒 适度方面，首先建立行人社交空间模型，并引入社会压力指标以量化机器人对人群的影 响；其次引入机器人动力学约束，将非线性运动约束纳入状态转移模型以提高轨迹平滑 度；最后综合考虑目标距离、安全距离和社交压力指数等多种因素设计奖励函数，以平 衡导航效率和社会价值。实验结果表明，所提出的算法在导航成功率和人群舒适度方面 优于基线算法，在标准场景中成功率达到了 99.8%。 （2）针对动态密集人群场景中机器人导航性能容易下降的问题，提出一种基于异 构神经回路策略的近端梯度优化(Structured Neural Circuit Policies with Proximal Policy Optimization, SNCP-PPO)算法。在该算法中，为更精确描述人机时空交互关系，构建反 映人机交互关系的时空图模型，将多个 NCP 构成的特征提取编码器，分别对时间和空 间特征进行提取，实现了机器人导航的时空推理，提高了其在动态复杂场景中的导航能 力。此外，为加快模型收敛，采用近端梯度优化(Proximal Policy Optimization, PPO)算法 在仿真环境中进行端到端的强化学习训练，大幅提高了数据利用效率和训练收敛速度。 II 在具有 10 到 20 人的动态环境中，SNCP-PPO 算法始终保持 90%以上的成功率，优于基 线算法，并且导航时间也比较短，更加适用于拥挤的人群场景。 （3）针对室内环境静态障碍物建模困难的问题，提出了一种具有粗粒度局部地图 （SNCP with coarse-grained Local Maps, LM-SNCP）的异构神经回路策略网络，该策略 融合了时空图和粗粒度局部地图两种表示形式，能够同时建模机器人与动态行人的交互， 以及处理静态的异形障碍物。时空图刻画了人机交互的时空互动模型，粗粒度局部地图

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则对障碍物的边缘和形状进行了编码，两者互为补充，赋予了 LM-SNCP 全面感知复杂 环境的能力。采用多进程技术并行采样环境数据，通过 PPO 算法和广义优势估计对 LMSNCP 进行端到端的强化学习训练，使其能够从复杂场景中学习出最优的导航策略。实 验结果表明，无论是人数还是障碍物数量变化，LM-SNCP 都能保持较高的成功率和效 率，为机器人在更普遍的场景中与人自然共存提供了一个范例。 上述研究通过构建人群导航仿真环境对所提算法进行了仿真验证，对导航成功率、 人群舒适度、平均导航时间等关键性能指标进行了评估，并在不同人群密度下测试了这 些算法的性能和效果，本文的相关研究成果可为移动机器人在实际动态人群环境中实现 高效、安全、平滑的导航提供了一定的理论基础和技术支持。

图 4-8 硬件实验环境

NOKOV 度量动作捕捉在研究中的应用摘录

在实验中，机器人使用 NOKOV 运动捕捉系统来定位自身位置和估计人类位置。参与实验的志愿者在场内随机行走，速度约为 1.0m/s。实验结果表明，SNCP-PPO 算法成功将仿真训练后的模型部署到真实环境中，在不同场景下，机器人可以朝着预设目标安全有效地导航，同时与周围人类保持安全距离。为了建议机器人的避障能力和导航能力，本节设计了三个场景，首先是三个志愿者和机器人分别站在实验场景的四角，然后向对角移动，此场景考验穿叉人群的能力；第二个场景为三人并排行驶，检验机器人绕过人群的能力；第三个场景为一个志愿者故意阻碍机器人移动，检验机器人局部避障的能力。

引用格式 田勇猛.基于神经回路策略的移动机器人导航算法研究[D].河南大学,2024.DOI:10.27114/d.cnki.ghnau.2024.003364.

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https://kns.cnki.net/kcms2/article/abstract?v=6h6U53PWxNTEC8joJm1_IPpTJAd1ZqgRtpE1arYlgddTbOD9NzV-mc7rilOd0U7xXohaMsNSs6hgwUrpEbSR84tTz21oI0IZmQpbHyXJB6TmOvdwBP97RmNn4AqmIeoTecKr6YaogHf2hPjaImLJMbt5qKiJDuMj4ckgDUYvfIlGHabYpaDX0kcqPMVDJKUC&uniplatform=NZKP

基于视-触融合的轮式星球车防自陷语义导航研究

关键词

轮式星球车;非几何障碍;轮-壤作用参数;语义建图;自主探测导航;

摘要

为克服深空通信延迟,降低对人工干预的依赖,星球车需自主导航以独立执行探测任务,但现有的星球车自主探测系统主要针对几何障碍,难以有效识别和规避非几何障碍。传统触觉感知依赖复杂力学模型,实时性不足,且仅在星球车进入危险区域后生效,缺乏预见性;路径规划多依赖遥操作,自主决策能力有限。本文提出了一种视-触融合语义导航框架,提升了视觉预测、触觉感知和自主决策能力,视觉预测可通行区域,触觉感知非几何障碍,完成了安全高效的自主导航。 提出了一种基于统一轮-壤接触力学模型(Unified Wheel-terrain Interaction Model,UWTIM)的触觉感知方法,可实时提取轮-壤作用参数,并测定了防止星球车发生自陷的沉陷阈值;分别制作了星球真实地形和模拟地形的语义分割数据集,训练了基于 Transformer 框架的语义分割模型 GA-Nav 以提供语义信息,GA-Nav 在真实地形上的分割平均准确度(m Acc)为 81.03%,在模拟地形上的 m Acc 达 96.17%;改进了相机-激光雷达融合技术用于构建混合视觉感知框架,有效点云数量提升了 1.5 倍。融合深度点云与语义信息得到了深度语义点云,丰富了混合视觉感知框架得到的地形特征,将深度语义点云插入到 Octo Map 结构中构建了 3D 语义地图,投影后得到了用于决策规划的 2D 语义地图。 改进了传统的动态窗口算法(Dynamic Window Approach,DWA),提出了正负速度空间中速度采样轨迹生成方法和变长度等曲率预测轨迹生成方法,建立了包含目标距离、语义信息、航向偏差和最优线/角速度约束的代价函数,使星球车能够根据视-触觉反馈动态规划路径以避开非几何障碍。 开发了单轮具备旋转、摆动和抬升功能的轮式星球车原理样机,并通过实验确定了松软地形的沉陷阈值;混合视觉导航实验中,星球车选择了代价较低的路径,验证了混合视觉导航框架的有效性;视-触融合导航实验中,星球车能够有效识别非几何障碍并脱离危险区域,证明了视-触融合语义导航框架的有效性。

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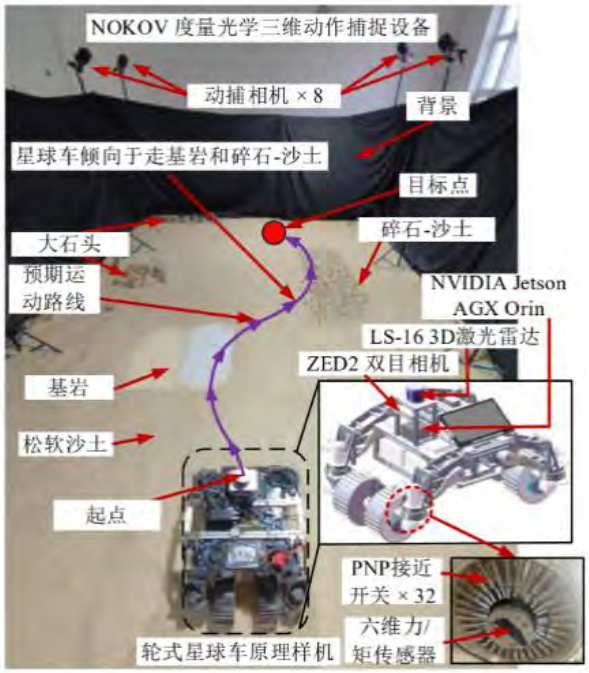

图 5-1　试验场地布置

NOKOV 度量动作捕捉在研究中的应用摘录

这个实验主要是为了验证视觉导航下，混合视觉感知系统和改进 DWA 规划算法的有效性。自定义的相机-激光雷达融合保证星球车能观测到几何和非几何障碍物，几何地形有大石头，露头岩层；非几何障碍物如基岩、碎石-沙土、松软沙土三种地形；在激光雷达的观测下不同的非几何地形无法区分，语义分割模块能分割几何和非几何地形，且由于不同的非几何地形颜色纹理不同，语义分割模块也能够区分开来，让星球车具备区分不同非几何障碍物的能力，然后根据 F-LOAM 提供的定位信息和计算出的里程计信息构建 3D 语义地图，按照表 4-3 代价投影得到 2D 语义地图，然后使用改进的 DWA 算法完成混合视觉导航。实验布置了 6×8 m2 的沙槽地形，沙槽深度 30 cm，周围用黑色幕布作为背景，且将 NOKOV 度量光学三维动作捕捉设备的 8 个摄像头均布在沙槽四周，动捕系统能够以 60 Hz 的频率，实时获取星球车上的每个 Marker 反光标志点的运动位置、速度等信息，将 4 个 Marker 点均匀安装在星球车车体四周，可以通过求取各 Marker 点速度和位置的均值，获取星球车的实时位置和速度信息。

引用格式　黄振振.基于视-触融合的轮式星球车防自陷语义导航研究[D].哈尔滨工业大学,2025.DOI:10.27061/d.cnki.ghgdu.2025.003088.

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基于数据增强和数据迁移的运动想象脑电分类研究及应用

关键词

脑机接口;运动想象;数据增强;数据迁移;深度学习;共享控制;

摘要

基于脑电图(electroencephalogram,EEG)的运动想象(Motor Imagery,MI)分类任务是脑机接口(Brain-Computer Interface,BCI)领域的一个重要研究方向。然而,EEG 信号的低信噪比、数据收集处理的高成本和个体差异性大,导致模型泛化能力弱,影响了 MI-BCI 系统的实用性与便捷性。本文研究了基于数据增强和数据迁移的 MI-EEG 信号分类及其结合共享控制策略的应用。主要工作如下: 1.提出基于数据增强和深度学习的 MI-EEG 解码模型。首先,采用连续小波变换的时频分析技术,提取 MI-EEG 信号的时间-频率特征,将一维时间序列转变为二维时频图,突出 EEG 信号的频率特征。然后,为了解决因数据量小导致卷积神经网络(Convolutional Neural Networks,CNN)过拟合的问题,提出了基于梯度惩罚的 Wasserstein 距离生成对抗网络(WGAN-GP)的数据增强方法,对 MI-EEG 小规模数据集进行数据量的扩充。同时,设计了一个轻量化的 CNN 网络,针对于 MI-EEG 数据规模,平衡模型运算的参数数量,并分层提取 MI-EEG 数据的时间和频率特征。对于整体解码模型,通过与先进方法的对比以及可视化说明,证明了其可行性和高效性。这一模型解决了 MI 数据量不足导致分类网络训练困难的问题,并且提高了分类准确率以及增强了网络的泛化能力。2.提出了基于多源数据迁移的跨被试 MI-EEG 解码方法。通过分布结构相似性和特征判别相似性的双重度量,量化源域与目标域的相似程度。筛选出与目标被试相似的被试数据,组成最优训练集,从而提高跨被试分类的准确性。并将整体跨被试解码模型与其他现有方法进行了对比,验证了方法的有效性。同时,通过消融实验,进一步探索数据增强和多源数据迁移在整体模型中的作用。 3.提出了基于 MI-BCI 解码模型的无人机共享控制系统。为了提高 MI-BCI 实际应用的控制效率和成功率,针对 MI-BCI 系统设计了一个共享控制策略,用于控制无人机实现目标点的飞行任务。通过实验证实了 MI-BCI 系统结合共享控制策略的可行性,为 BCI 的共享控制范式提供了新的技术路径。

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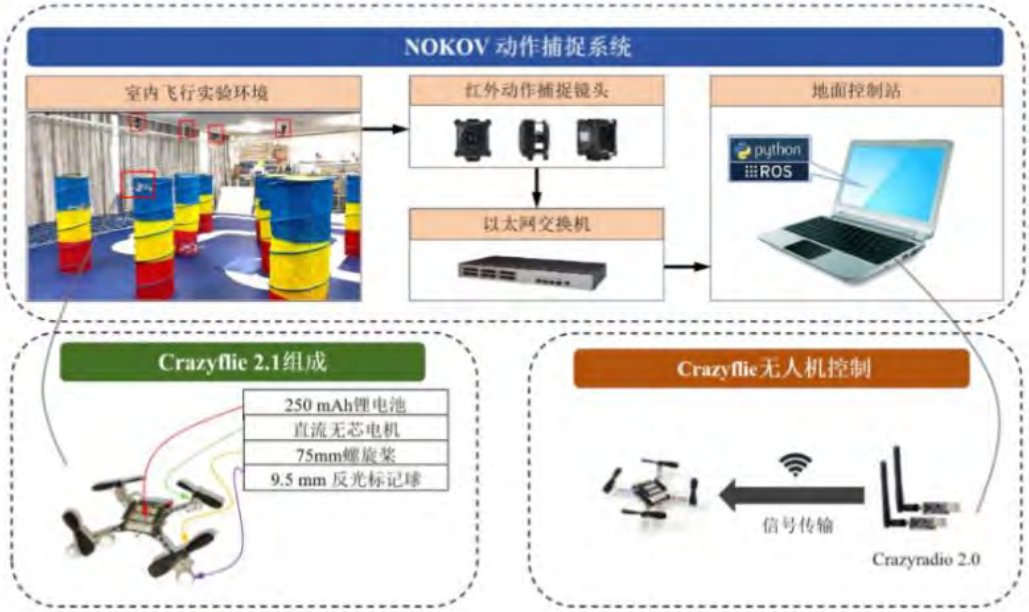

图 5-3 无人机平台构成

NOKOV 度量动作捕捉在研究中的应用摘录

> *5.2 无人机平台介绍*
> *如图 5-3 所示，本研究构建的无人机飞行实验平台基于 Nokov 光学三维动作捕捉系统、ROS 地面控制站和 Crazyswarm 无人机平台三大核心模块。实验环境配置了 16 个顶部均匀分布的红外捕捉镜头，配合以太网交换机和数据处理软件，实现对无人机运动轨迹的毫米级精准定位。实验对象选用 Crazyflie 2.1 四旋翼无人机，该机型搭载了多轴惯性传感器组（包含加速度计、陀螺仪和气压计）以及特制的动捕标记甲板。其主控采用 STM32F4 微处理器（168MHz 工作频率），负责飞行器的状态估计与底层控制。系统工作原理为：地面控制站综合处理光学捕捉数据后生成加速度指令，经坐标变换后形成完整的位姿控制指令，最终通过 2.4GHz 无线通信模块（Crazyradio2.0）将指令下发到无人机中。*

引用格式 李佳河.基于数据增强和数据迁移的运动想象脑电分类研究及应用[D].天津工业大学,2025.DOI:10.27357/d.cnki.gtgyu.2025.000883.

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基于无人机的离散结构自主建造技术初探

关键词

无人机建造；移动机器人；现场建造；离散单元；协同策略

摘要

随着以 3D 打印为代表的增材制造技术的应用,机器人辅助的现场数字化建造技术为未来建筑产业发展开辟了新的发展方向,也带来了对于设计方法、系统控制等一系列挑战。近年来由于无人机 (UAV) 相关技术的成熟,其在建造业中的应用研究已成为拓展可移动机器人数字建造平台的重要发展方向。通过一个由无人机组群自主建造的离散结构单元系统的研究性项目,试图探讨无人机自主建造离散单元组合的复杂空间结构体系的可行性,建立适用于无人机自主建造的设计方法、实时控制系统和可视化界面平台,并由此总结出适用于多台无人机协同的现代化数字建造中的关键技术。通过现场双机协同建造实验的具体分析,展示研究中实验环境建立、整体结构生形、离散单元设计、建造时序优化和双机智能协同的无人机离散单元建造的整体流程和优化策略,为集群智能体自主建造提出了进一步研究的思路和方法。

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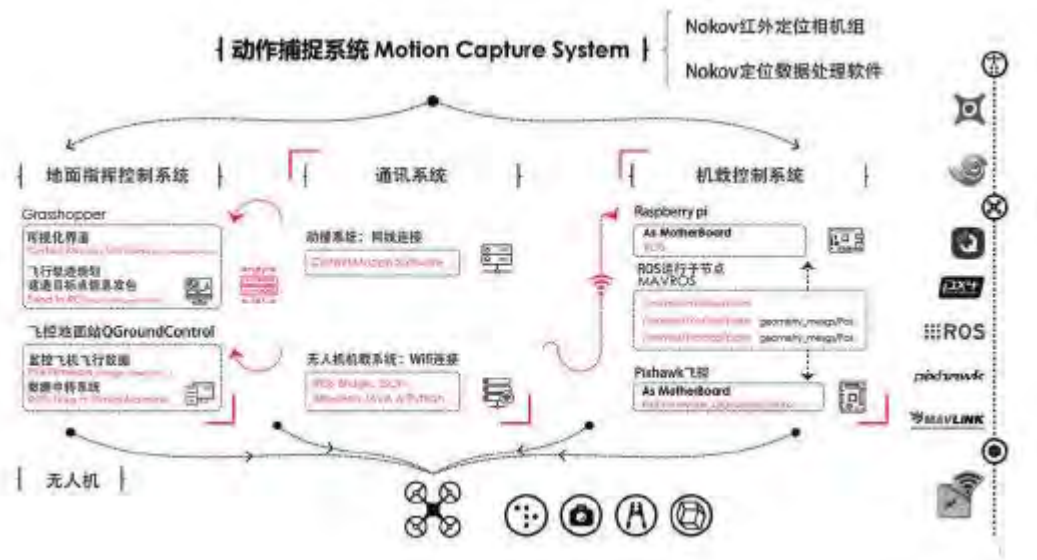

NOKOV 度量动作捕捉在研究中的应用摘录

无人机系统运动控制的复杂性远高于地面固定的机械臂数字建造系统，因此需要多终端、多传感器的协同运行。本项目将机器人路径规划平台与机器人运动控制平台分离，除在数字建筑设计中常用的 Grasshopper 平台之外，引入 ROS 开源系统（RobotOperatingSystem）\[13]，实现 Windows 和 Linux 操作系统之间的连接，通过建立 ROS 模块和 Grasshopper 之间不同软件平台的通信与数据转换方法，搭建适用于无人机建造复杂场景的自主建造技术框架（图 9）。完整的无人机自主建造系统由无人机空间位姿反馈和地面站轨迹规划控制两部分组成。在位姿控制部分利用无人机控制领域常用的开源 PX4 解决计）、磁力计、气压计和空速计等传感器系统，综合处理无人机实时的局部姿态信息。全局定位控制采用了基于光学红外相机的动作捕捉系统（项目运用 Nokov 动作捕捉系统），代替室外常用的 GPS 定位系统对无人机的实时位置进行跟踪，以满足室内无人机稳定悬停的作业需求，同时将无人机坐标信息传回地面站计算机

引用格式 郭喆,陆明,王祥.基于无人机的离散结构自主建造技术初探[J].建筑技艺,2019(09):40-45.

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基于无人机集群的电磁环境地图构建方法研究

关键词

无人机集群；电磁环境监测；电磁环境地图；狼群算法；深度学习；

摘要

电磁环境地图通过从多个维度对电磁环境进行描述，可视化展示电磁能量分布、频谱资源分布等信息。通过构建电磁环境地图，可以获取电磁环境中的电磁辐射源、电磁传播途径、空间环境实体等信息，从而实现对电磁环境态势的整体感知。为了实现电磁环境地图的构建，需要首先收集空间中的电磁信息。借助于无人机机动灵活便于布置的优势，可以实现未知区域中电磁信息的获取，但单个无人机所能搭载的测量设备有限，所能获取的电磁信息数据很少，因此需要利用无人机集群提高电磁信息的获取量。本文研究了基于无人机集群的电磁环境地图构建方法，具体内容如下:

电磁环境监测主要是通过收集环境中的各类电磁辐射源信号，为后面电磁环境地图构建等技术的应用提供数据支持。因此需要无人机集群对电磁辐射源进行搜索监测。针对此问题，设计并实现了基于数字信息素的狼群算法用于无人机集群执行电磁环境监测。主要研究内容为:提出了基于数字信息素的狼群算法，用于优化无人机集群的航迹，提高搜索监测的效率。针对监测过程中单个无人机获取信息的能力有限，为了利用集群获取的局部信息构建全局地图，提出了一种基干狼群社会结构的分布式数据聚合方法，将利用无人机集群获取并进行聚合之后的电磁信息数据保存到集群的领航者中，用于实现整个区域的电磁环境地图高精度构建。

由于无人机集群在电磁环境监测中仅能获取部分电磁信息数据，为了构建高精度的全局电磁环境地图，针对无人机集群在领航者处保存的电磁信息数据，设计并实现了基于部分卷积和注意力机制的电磁环境地图构建方法。主要研究内容为:考虑输入电磁信息数据的不完全性，把部分卷积和注意力机制加入到 U-net 网络架构中，设计了一种新的电磁环境地图构建方法。通过仿真实验验证了所设计方法与插值方法以及生成对抗网络方法相比在构建精度方面的优越性。同时，对于无人机集群基于不同监测方式下获取的数据进行电磁环境地图构建的精度进行比较，验证了基于数字信息素的狼群算法以及分布式数据聚合方法的有效性。为了验证本文所提出方法的合理性，本文以 WiFi 定向天线作为辐射源构建空间中电磁信息分布，通过动作捕捉系统为无人机集群提供室内定位，以 ESP-8266 芯片作为数据测量设备，搭建了以四旋翼无人机和测量芯片为主要实验展示载体的半实物仿真平台。通过该平台验证了本文方法的有效性。

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NOKOV 度量动作捕捉在研究中的应用摘录

平台的软件主要由 Nokov 工作站软件、飞控工作站软件、无人机固件控制软件组成。其中，Nokov 工作站软件主要实现操控动作捕捉系统及数据获取处理，用于获取无人机的位姿信息；Nokov 工作站软件主要为由度量开发的 Seeker1.6 动作捕捉系统软件组成，支持系统的标定、校正及数据采集、导出工作，并提供实时 SDK，可将数据实时导入 Matlab、C++、Linux、Simulink 等平台当中。

引用格式 李彤.基于无人机集群的电磁环境地图构建方法研究[D].电子科技大学，2022.DOI：10.27005/d.cnki.gdzku.2022.001590.

链接

https://kns.cnki.net/kcms2/article/abstract?v=W694F5cljyACtT6DwjK9dC8dtLUvVE_Ig2itkhMLP1BdsS042WuYSliUFXdmpINLsiLR4SBy1itA7wiL0YifZ4gYb44E0FpkjN5Rkar8OKdysITRMvE5NMUEGVJMK5Krv26JolwjijW4FtNSi-bwdUb84NKsBegwAWc_WMKBeIjpL2MZMIdAZcHcgKt4wqvFav8YHmZX-1s=&unip

基于虚拟现实和眼动的人-集群机器人交互方法

关键词

人-集群机器人；交互方法；，集群机器 VR 交互；眼动追踪；集群行为控制

摘要

操作员对集群机器人实施远程控制时面临被控对象众多、群体态势感知困难、集体行为指控不易等诸多挑战，使得手动遥控等传统交互方式无法实现高效、灵活、强沉浸感的人-集群机器人交互。为此，提出一种基于虚拟现实（VR）和眼动追踪的人-集群机器人（HSI）交互方法。首先，构建集群机器人 VR 交互场景并采集操作员的眼动数据；其次，解析获得瞳孔坐标、注视点等眼动特征，据此生成集群机器人的运动控制指令；最后，开展了真实集群机器人集群漫游、集群目标追踪及集群轨迹跟踪交互实验。机器人实验结果表明，该方法可实现灵活、便捷的人-集群机器人远程交互控制，这为人与集群机器人的共融协作提供了一种新的途径。

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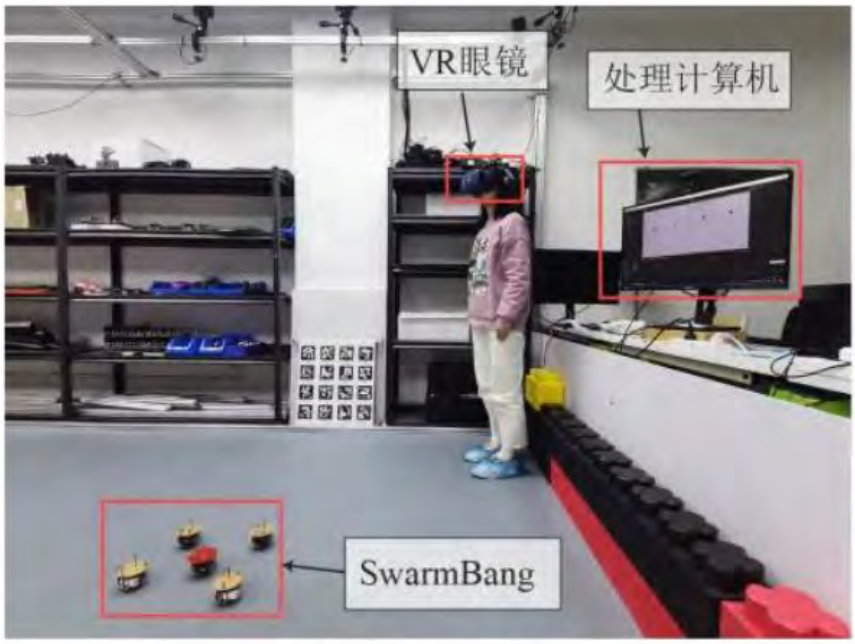

(a) 真实实验环境

NOKOV 度量动作捕捉在研究中的应用摘录

人-集群机器人交互实验的环境如图 6(a)所示，包括 5 台 SwarmBang 机器人，NOKOV 动作捕捉定位系统，VR 交互系统及处理计算机。搭建集群机器人及其作业环境的 3D 虚拟现实场景，并将其显示至操作员所戴的 VR 眼镜中，通过动作捕捉系统建立真实机器人运动状态与其数字孪生主体之间的状态互联，在 VR 场景中实时更新机器人运动状态，提高操作员的沉浸感和集群态势的感知效率。

引用格式 许明玉,雷小康,段中兴等.基于虚拟现实和眼动追踪的人-集群机器人交互方法[J].信息与控制,2024,53(02):199-210.DOI:10.13976/j.cnki.xk.2023.2548.

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具有执行器故障的四旋翼无人机自适应鲁棒滑模控制

关键词

四旋翼无人机；参数不确定性；外部干扰；执行器故障；自适应非奇异快速积分终端滑模控制

摘要

针对四旋翼无人机飞行中的参数不确定性、未知干扰和执行器故障的影响，提出一种自适应非奇异快 速积分终端滑模控制器（ANFTSMC）。通过建立带外部干扰和故障状态的无人机模型，并考虑系统的陀螺 效应因子与风阻系数的不确定性影响，提出了 ANFTSMC 控制器。同时，设计了自适应律来估计系统参数、 干扰及故障信息。为了保证闭环系统的稳定性，将未知集总扰动的上界作为切换增益。通过仿真实验和样机 实验验证，结果表明所提出的控制方案在有效性和鲁棒性方面优于快速终端滑模控制（FTSMC）和终端滑 模控制（TSMC）。

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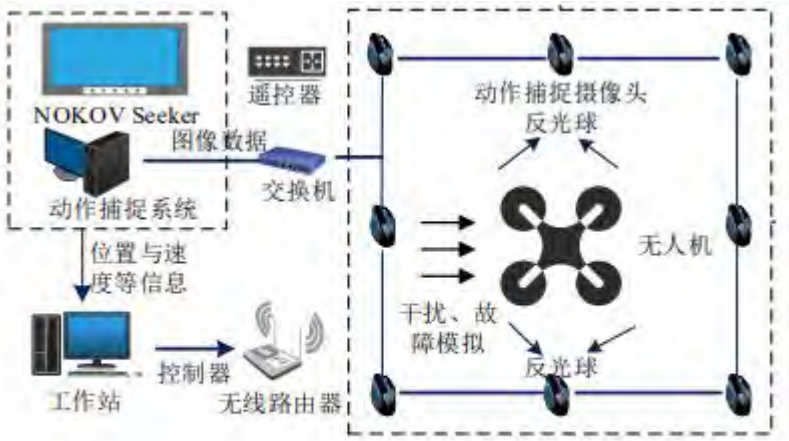

图 9　实验平台示意图

Fig.9 Schematic diagram of the experimental platform

NOKOV 度量动作捕捉在研究中的应用摘录

为验证本文算法的有效性，进行了室内飞行实验。实验平台包括 i7-9700K 处理器的工作站、（安装 Ubuntu 与地面基站软件，用于控制无人机并接收数据）、运动捕捉系统（包含摄像头、交换 机和 ZVR Goku 软件，通过采集反光球数据计算 无人机位置与速度并发送到工作站）、遥控器（用 于在异常情况下接管无人机控制）。实验平台示意 图如图 9 所示。

引用格式 王君,骆明敏.具有执行器故障的四旋翼无人机自适应鲁棒滑模控制[J].飞行力学,2025,43(03):49-55.DOI:10.13645/j.cnki.f.d.20250214.004.

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考虑多个时滞的无人机集群编队算法研究

关键词

无人机；时滞系统；多智能体系统；编队；碰撞避免

摘要

如今,社会分工逐渐精细化。各行业领域,如物流运输、流水线装配等为追求效率的提高已逐渐通过各种智能装备替代人力的参与。近年来,作为先进装备代表之一的无人机因其灵活性高、作业不受限于地形等优势在影视摄像、搜索救援等方面大放异彩。随着无人机技术的不断发展,人们赋予给无人机的任务种类也越来越多样。然而,为保证无人机的灵活性,机体体积受限导致单个无人机的能力始终有限,且存在搜索范围小、环境适应能力低和持续作战时间短等问题。为此人们参考自然界中动物成群合作的思路,通过无人机集群控制技术将众多能力单薄的无人机集结起来以适应不同类型任务。而在通信过程中不可避免地存在时滞,这对无人机支持类似依赖远程控制、运行速度高的作业任务产生了极大的影响。不仅如此,当无人机之间通信存在间接交互关系时,可能会在时滞系统的最高阶项中引入时滞,从而演变成为更加棘手的中立型时滞系统。本文通过介绍小时滞效应,揭示了中立型时滞与滞后型时滞系统的本质区别。由于这一独特的特性,中立型时滞系统表现出一种难以捉摸的稳定性特性。更糟糕的是,随着时滞数量的增加,中立型时滞系统的稳定性分析也变得更加复杂。为此,本文提出了一种新的频域分析方法,通过在两个任意选择的时滞和其他时滞不变的情况下,提取稳定性转换超曲面的二维截面,并顺带确定了与这两个时滞域相关的频率集的精确上界和下界。利用 Dixon 结式理论对特征方程通过转换所得的拟多项式进行求解。通过扫描获得的频率区间,确定了二维稳定性转换超曲线的完整集合。在此基础上,通过使用特征根聚类处理范式获得了中立型时滞系统精确的稳定分布图。最后,通过一个示例并结合数值算法证明所提出方法的准确性和高效性。考虑无人机集群控制过程中的时滞来源可能,从无领导情况开始讨论并借鉴领航者-跟随者法思想完成无人机集群编队控制律的设计。在对系统进行关于时滞的稳定性求解问题中,通过引入因式分解简化方法对所建立的无人机集群系统进行解耦降阶成由若干个二阶及四阶子系统组成的集合以降低计算复杂度。还通过介绍无人机集群控制中的两个前提条件,即可一致性及可追踪性性质,为后续所提出的强鲁棒性新型无人机编队控制算法作铺垫。除此以外,通过借鉴人工势场法思想引入常数强迫项及碰撞避免的斥力场,由此完成了无人机集群控制中的协同、跟随、编队、碰撞避免四个重要方面的需求。通过合理的实验设计及结果分析证明了本文所提的编队控制算法的正确性。

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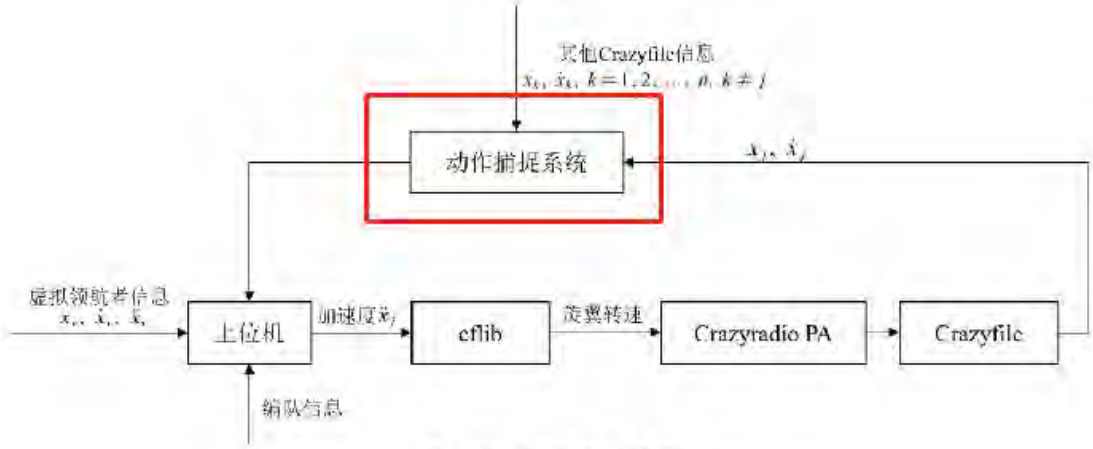

图 4-3 实验平台架构

NOKOV 度量动作捕捉在研究中的应用摘录

利用 NOKOV 动作捕捉系统对全局空间进行标定并且构建一个全局参考坐标系。动作捕捉系统经过拍摄后计算得出各个无人机的绝对位置及速度，将其发送至上位机中，经过时滞处理后获得各个无人机指定时滞前的位置及状态信息，最后再根据本文所提及的算法，将各个无人机的位置及速度按照邻接矩阵所定义的关系进行相应的联系及计算。

引用格式 钱浩琛. 考虑多个时滞的无人机集群编队算法研究[D]. 哈尔滨工业大学,2021.DOI:10.27061/d.cnki.ghgdu.2021.006709.

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面向大规模地下空间的多智能体端边协作全局 SLAM 方法

关键词

多模态融合;即时定位与建图;超宽带定位;端边协作;多智能体协同;

摘要

随着地下空间开发不断朝着深部化、大型化与无人化方向发展，移动机器人在地下探测及救援等方面发挥着重要作用.即时定位与建图（Simultaneous Localization And Mapping,SLAM）作为移动机器人的基础，为其自主导航与安全避障提供了可靠支撑.针对大规模地下空间传感器退化、计算瓶颈以及移动机器人感知范围受限且累积漂移严重等挑战，提出了超宽带（Ultra-WideBand,UWB）紧耦合的多智能体端边协作 SLAM 方法（Robots-edge Collaborative SLAM,Re-CoSLAM）.本文在边缘辅助的多模态 SLAM 框架基础上，结合误差状态卡尔曼滤波，设计了 UWB 紧耦合绝对位姿估计方法，有效提升了全局定位性能.进一步，基于 UWB 全局定位，建立了可扩展的多智能体协同 SLAM 框架与自适应传输机制.为了保障全局一致性，根据多智能体之间的 UWB 距离测量，提出了相对距离约束的联合位姿图优化方法 .此外，考虑到边缘节点的计算瓶颈问题，设计基于请求优先级的任务调度策略，以减少排队延迟并提高跟踪精度.本文在 3 台搭载英伟达板载计算机的移动机器人和 1 台边缘计算节点上部署 Re-CoSLAM，并在室内走廊、地下车库与地下巷道场景下开展了广泛的实验与评估.结果表明，Re-CoSLAM 可实现 7.3 cm 的绝对定位精度与 13 帧/秒的运行速度，定位误差比现有方法降低了 50%以上.

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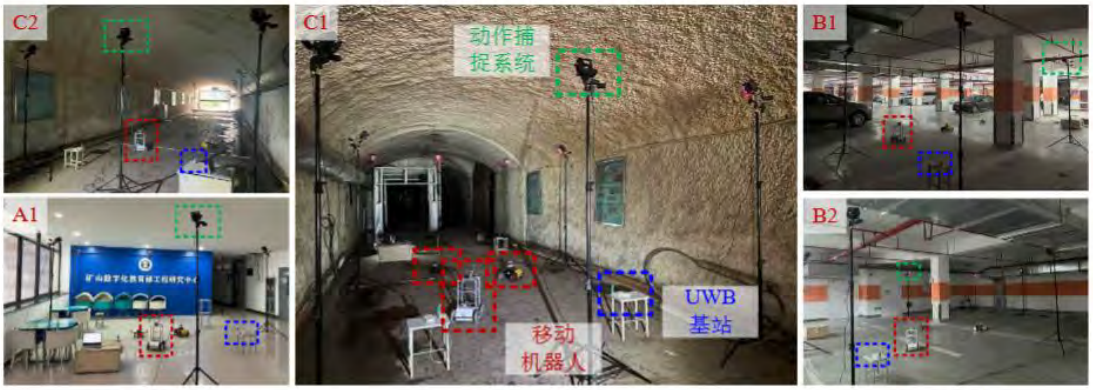

室内场景　　地下巷道　　地下车库

图6　不同实验场景与设备

NOKOV 度量动作捕捉在研究中的应用摘录

> *实验场景与设备.基于上述实验设置，本文分别在典型室内走廊、地下车库以及传感器退化的地下实验室巷道场景中开展实验与评估，如图 6 所示.在不同场景下均布设了 4 个由时域公司（Time Domain）生产的 P440 UWB 基站，用于建立统一的全局坐标系.同时，为了获取移动机器人的位姿真值，本文采用度量科技公司（NOKOV）的三维光学动作捕捉系统，通过红外光学镜头捕获反光标志点位置，以其提供的亚毫米级定位精度评估所提方法的性能，而影响其定位精度的因素主要包括镜头分辨率、镜头视场、标定质量以及镜头数量.在本实验中，采用了 8 个红外光学镜头，其分辨率和视场分别为 1280 × 1024 与 56° × 46°。*
> *NOKOV 的部署主要在于使用前的镜头标定，以捕获反光标志点在全局坐标系的位置.根据标定结果，其定位误差不超过 2 mm.由于红外光学镜头数量有限，导致其捕获位姿真值的范围受限，其最大范围不超过 10 m.本实验旨在验证多智能体协同 SLAM 的可扩展*

引用格式 张奎元,张启亮,陈朋朋,等.面向大规模地下空间的多智能体端边协作全局 SLAM 方法[J/OL].电子学报,1-13[2026-01-20].https://link.cnki.net/urlid/11.2087.TN.20251215.0909.002.

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融合卡尔曼滤波和时序卷积网络的 UWB 定位算法

关键词

超宽带;时间卷积网络;室内定位;随机误差;卡尔曼滤波;

摘要

超宽带（UWB）技术凭借其厘米级测距精度和卓越的抗干扰能力，在室内高精度定位领域受到广泛应用。然而，复杂的室内环境导致 UWB 定位系统仍存在显著的随机误差问题。针对这一挑战，本研究提出了一种融合卡尔曼滤波（KF）和时序卷积网络（TCN）的定位算法（KF-TCN）。首先获取基站与移动标签之间的原始距离测量数据，并构建具有时序特性的数据集；随后利用卡尔曼滤波对测量数据中的线性噪声进行有效抑制；最后通过设计的 TCN 网络对时序特征进行深度分析，实现对位置的精准估计。仿真实验与实地测试结果表明，所提出的 KF-TCN 算法在随机误差抑制方面表现突出，相较于 KF-CNN、TCN 以及 CNN 算法，其定位精度分别提升了 31.93%、57.45%和 65.08%，为 UWB 定位提供了一种新的解决方案。

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图 4 实测实验场景

NOKOV 度量动作捕捉在研究中的应用摘录

2.2 实测实验
为验证算法实际应用的可行性，在河南理工大学北校区地下防空洞开展了实地测试以验证其性能。实验场地大小为 6mx6 m，采用 DWM1000 PG4.6 型 UWB 测距模块构建定位系统，其中 4 个模块作为固定基站，1 个模块作为移动标签安装于多传感器集成的无人平台上。为确保测试精度，使用定位精度达亚毫米级的北京度量 NOKOV 三维动作捕捉系统标定基站坐标，并同步采集移动标签的基准坐标数据作为真值。测试过程中，移动平台沿预定轨迹运行，同步采集 UB 测量数据与基准坐标数据，实验场景如图 4 所示。四个基站 4、B、CD 的坐标分别为(130.5.98.8)、(126,545.5)、(618.5,539.5)和(624.9.117)，单位为厘米。

引用格式 贺刘辉,连增增,赵辰瑞,等.融合卡尔曼滤波和时序卷积网络的 UWB 定位算法[J/OL].测绘地理信息,1-5[2026-01-20].https://link.cnki.net/urlid/42.1840.P.20250903.1422.002.

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融合预瞄机制的移动机器人预设性能视觉伺服控制策略

关键词

移动机器人;轨迹跟踪;预设性能控制;视觉伺服;预瞄机制;

摘要

大型航空结构件的自动化运输中，基于图像的移动机器人跟踪变曲率轨迹，存在图像可见性约束和转向角速度约束问题。本文提出一种融合预瞄机制的预设性能视觉伺服控制策略，通过误差变换函数将归一化平面受限误差转换为无约束误差，并引入预设性能函数，确保误差按预设性能收敛，保障图像中特征点的可见性。同时，构建"双区域"特征提取方案，结合曲率驱动的自适应预瞄距离模型，提前修正状态反馈，有效抑制角速度突变。通过 Matlab/Simulink 仿真与实物实验对该方法进行验证，结果显示，该方法很好的将误差约束在预设曲线内，并且融合预瞄机制后，显著提升了移动机器人的跟踪精度与运动平稳性。

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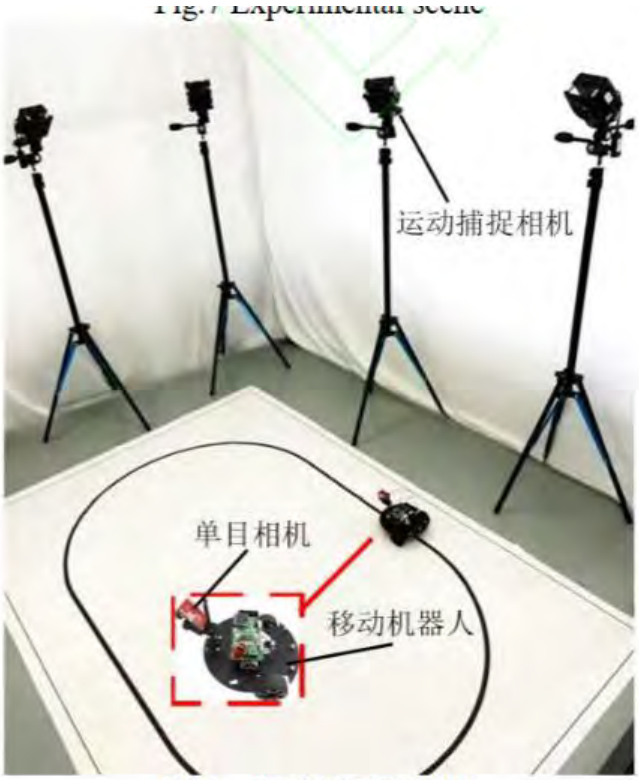

图 8　实验场景布置图

NOKOV 度量动作捕捉在研究中的应用摘录

> *3.2 实物实验*
> *实物实验采用搭载视觉传感器的轮式机器人跟踪如图 7 所示轨迹，实验设置三组对照组，对比融合预瞄机制的预设性能视觉伺服控制(预瞄-PPC)、仅使用预设性能视觉伺服控制(PPC)和比例积分滑模控制(PISMC)\[20]三种控制方案。*
> *如图 7-8 所示，实验采用两条直线长 0.8m 和半径 0.63m 的两个半圆拼接而成的黑色色带。移动机器人主控器为 STM32 单片机，采用 OpenMV3 视觉传感器对获取图像信息。通过对图像进行二值化处理并提取色带中线作为参考轨迹。机器人运动的位姿数据采用 NOKOV 光学三维动作捕捉系统进行测量。*

引用格式 曹轶然,高磊,吴孟丽,等.融合预瞄机制的移动机器人预设性能视觉伺服控制策略[J/OL].中国机械工程,1-9[2026-01-20].https://link.cnki.net/urlid/42.1294.TH.20251107.1014.002.

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四旋翼无人机速度自适应运动规划研究

关键词

四旋翼无人机；运动规划；路径搜索；轨迹优化；速度自适应

摘要

四旋翼无人机具有灵活度高、机动性强、结构简单等优势，被广泛应用于侦察搜索、矿洞勘探、物流配送等军用和民用任务。在自动化、智能化、数字化时代驱动下，各行业对四旋翼的自主性和安全可靠性提出了更高要求，如何构建运动规划系统，生成无碰撞、平滑、可执行的高质量轨迹成为亟待研究和解决的挑战性问题。目前，尽管涌现了大量关于四旋翼运动规划的研究成果，但大多没有考虑环境安全裕度对飞行速度的影响，难以实现安全性与效率的平衡。鉴于此，本文以速度随环境自适应调整为导向，提出了基于二次规划、基于无约束优化以及基于无欧氏距离场的三种运动规划算法，实现了四旋翼安全可靠的自主飞行。本文的具体工作如下：

（1）基于二次规划的速度自适应运动规划。首先，提出了种自适应节点扩展的算法进行初始路径的搜索，在此基础上生成不含障碍物的安全飞行走廊。其次，采一用分段的Ｂｆｅｉｅｒ曲线描述轨迹，并将轨迹优化表述为个典型的二次规划问题。为了实现速度自适应，利用安全飞行走廊估计轨迹附近的安全裕度，并将其作为影响速度代价的因子。再次，为了使速度自适应策略适用于障碍物稀疏的场景，提出了一种后验的安全检测方法。最后，通过仿真实验和实物实验验证了所提算法的有效性，即速度能够随环境自适应调整。

（2）基于无约束优化的速度自适应运动规划。由于B样条曲线具有局部修改性、凸包性等优良特性，采用B样条曲线对轨迹进行数学描述。基于B样条性质和轨迹优一化需求，构建了个无约束优化问题框架。在该框架中，利用欧氏距离场提供的障碍物距离及距离梯度信息，设计了可随环境自适应调整的速度代价函数。求解无约束优化问题后，对轨迹进行安全性检测和动力学可行性检测，并从速度自适应的角度提出一了种新的时间分配方法。最后，在仿真平台中进行了感知范围受限的无人机自主避障实验，验证了所提算法的有效性。

（3）基于无欧氏距离场的速度自适应运动规划。为了降低运动规划的计算成本，采用障碍物内轨迹与无碰撞路径之间的差距代替欧氏距离场，以获取障碍物距离及距离梯度信息。在此基础上，构建碰撞代价函数，并将碰撞代价作为速度代价的影响因一子，从而提出种新的速度随环境自适应调整方案。最后，对所提算法进行了仿真实验与实机飞行实验测试，验证了算法的有效性。

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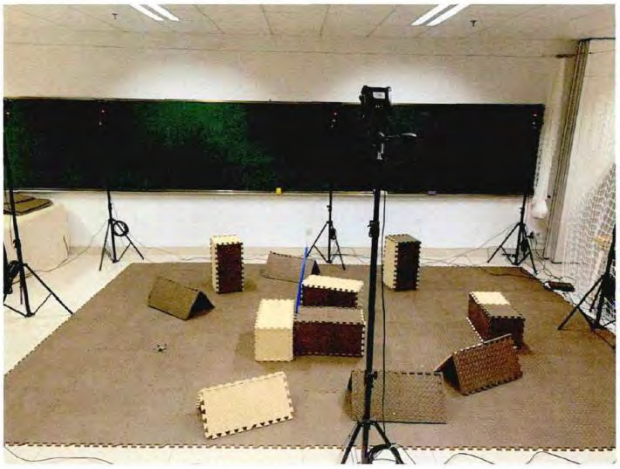

图 2-3 镜头排布方式和飞行实验场景

Fig.2-3 Camera arrangement and flight experiment scene

NOKOV 度量动作捕捉在研究中的应用摘录

定位系统采用 NOKOV 度量公司的光学三维动作捕捉系统，该系统主要由动作捕捉镜头、动作捕捉软件 X I N G 和动作捕捉附件组成。
本平台使用 8 个动作捕捉镜头搭建了 5 m x 6 m x 2.5m 的实验区域，并在 Crazyflie 上安装了 4 个反光标识点来获取位姿数据，图 2 - 3 展示了平台的镜头排布方式和飞行实验场景。

引用格式 赵畅.四旋翼无人机速度自适应运动规划研究[D].山东大学,2023.DOI:10.27272/d.cnki.gshdu.2023.002000.

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无人车多源传感器信息融合导航技术研究

关键词

无人车；惯性导航；超宽带；里程计；因子图；增量平滑优化算法

摘要

科技日新月异的今天，我们的生活越来越向智能化发展，无人车越来越走进我们的生活。同时这也带来了无人车的导航和定位问题，为了更好的对无人车进行导航和定位，针对单一传感器无法满足全天候、全天时、全地域、高精度定位与导航这一问题，本文的研究内容为无人车的多源信息融合导航。对于在复杂环境中可能会出现的环境因素改变，信息异步、时延等情况，构建了基于因子图模型的多源传感器信息融合框架，通过理论分析以及搭建实物平台对本文算法的各项性能进行讨论，主要完成了以下研究内容。

研究了多传感器理论和相关导航基础，对坐标系定义和姿态角表示方法进行了分析，以及惯性测量单元（IMU）、超宽带（UWB）、里程计（ODOM）的测量原理和定位技术。

阐述了图相关的概念、研究了贝叶斯网络和因子图模型。推导了无人车定位问题的概率模型，并转换成相对应的因子图模型。同时为了提高计算效率，引入了 IMU 预积分方法，建立起等效 IMU 因子；将传感器测量信息抽象成传感器因子，推导了最大后验概率的非线性最小二乘表示，并通过高斯牛顿法进行求解。

研究了两种基于增量平滑的优化算法，一种是基于 Givens 旋转的优化算法，通过 Givens 旋转变换对加入测量值的信息矩阵进行变换，变成上三角形式，但该方法需要周期性的批处理步骤，时间复杂度较高。另一种是基于贝叶斯树的增量平滑优化算法，该方法通过变量消元将因子图转换成贝叶斯网络，再将贝叶斯网络转换成贝叶斯树，该算法在保证精度的同时也具有实时性。

搭建了跑车实验平台，设计了实验方案，在定位效果，效率，鲁棒性能上对算法进行了讨论，通过分析定位误差，表明算法具有一定的实时性，准确性，提高了定位精度和可靠性。

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(a) (b)

图 5-7 动捕系统和刚体安装位置

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图 5-6 中 红色圈住的部分上边 是 UWB 传感器，下面放置的是 IMU 传感器， 同时对于真值的获取，本实验采用实验室的动作捕捉系统（ Nokov），通过布置在上面的 16 个摄像头对 小车上三个小球形成的 刚体进行识别而 确定了位置的真实值，如图 5-7(a)，5-7(b)红线圈出部分所示，动作捕捉系统的定位精度达 到了毫米级别，是作为小车运动轨迹真值的 最佳选择。

引用格式 沈贺兵.无人车多源传感器信息融合导航技术研究[D].哈尔滨工业大学，2021.DOI：10.27061/d.cnki.ghgdu.2021.004020.

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相对位姿估计系统设计及其在机器人自主导航中的应用

关键词

相对位姿估计；多机器人系统；自主导航；

摘要

近年来,在无人机、无人车等领域,单机器人技术飞速发展,越来越多的学者开始致力于研究多机器人协同工作。其中,相对位姿估计是多机器人系统中一个亟待解决的难题,稳定、准确、快速的估计出机器人之间的相对姿态可以显著提高机器人协作质量。目前,国内外研究学者相对位姿估计问题上提出了诸多方案。一些研究提出将 SLAM 系统同距离等传感器融合的解决方案,但这些方案受限于 SLAM 技术的弊端,依赖于环境特征的同时会占用较多的计算资源。也有一些研究针致力于使用距离方位传感器融合的解决思路,这些方案需要运动激励并且在一些运动模式下会出现退化现象,或者需要比较大的安装平台。此外,还有学者提出给机器人配备人工标签的思路,但目前提出的一些设计方案仅能在很短的范围内有效工作,这对实际场景中的应用带来了很大的困难。本文专注于多机器人系统中的相对位姿估计问题,设计了一种基于多种传感器融合的相对位姿估计系统,包括硬件和算法两部分。硬件系统主要包括红外 LED,红外鱼眼相机,IMU 和 UWB 四大模块。算法上,本文首先利用单次的传感器数据测量解算相对位姿,同时利用误差状态卡尔曼滤波器来抵抗传感器噪声对估计精度的影响。当多机器人系统中机器人数目达到三个及以上时,本文设计了一种利用单帧数据的位姿图优化算法来进一步提高系统精度。实验结果证明,本文的相对位置估计误差在 0.113 米 ~ 0.161 米(中位数),相对旋转估计误差在 0.773° ~ 1.517°(中位数)。此外,在特殊场景(黑暗,长距离,大姿态和非视距)下也具有稳定的工作性能。相比于目前已有的基于人工标签的设计方案,本文设计的系统有效提高了工作范围,实验中测试最远的工作距离可以达到 27.5 米。在计算资源本占用方面,本文的系统低于基于 SLAM 系统的解决方案,经测试在 NUC-i5 计算平台上,本文 ID 识别图像处理时间低于 2 毫秒,两机算法时间低于 1 毫秒,三机及以上位姿图优化算法低于 3 毫秒。此外,本文将设计的相对位姿估计系统同目前的一些自主导航方案结合起来,通过利用相对位姿进行栅格地图的共享从而降低一部分机器人构建地图的算力消耗。同时,本文在 Robo Master 小车上进行实验验证了方案的可行性。

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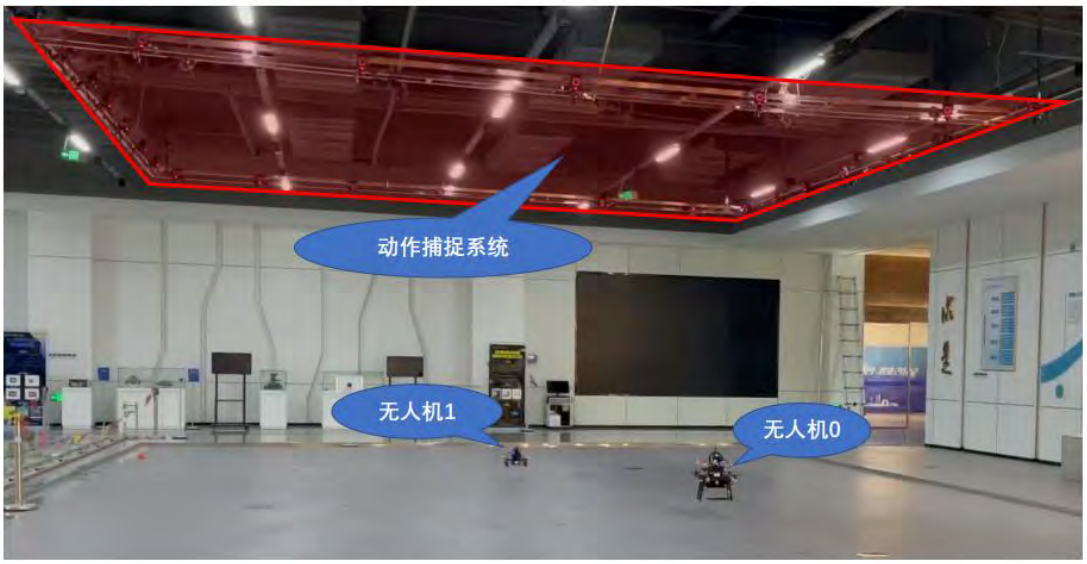

图 3.8 两机精度实验场景

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为了测试设备的相对位姿结果估计的精度，本文搭建了如图 3.7 所展示的无人机平 台进行实验，无人机的轴距为 330 毫米。本部分实验主要验证本文提出的单帧数据相对 位姿解算和改进 ESKF 算法的精度。本文利用 NOKOV 公司的动作捕捉系统获得无人机在动捕参考系下的位姿真值，经过一定的转化可以得到两个机器人之间的相对位姿的真值。

引用格式 寻芝任.相对位姿估计系统设计及其在机器人自主导航中的应用[D].浙江大学，2023.DOI：10.27461/d.cnki.gzjdx.2023.000058.

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巷道凿岩机器人地图构建及自主导航技术研究

关键词

自主导航；同步定位及地图构建；激光惯性融合；路径规划

摘要

煤炭作为我国重要的能源，煤炭开采技术的智能化发展是其高质量发展的必由之路。煤矿机器人智能化是拉动煤炭产业高质量发展的新引擎，具有一定的经济效益与社会效益。凿岩机器人作为煤矿机器人中重要的一员，具有广阔的应用场景，其工作环境的三维地图构建及其自主导航是智能化的关键环节。本文提出一种基于激光雷达与惯性传感器的巷道地图构建及凿岩机器人自主导航策略，通过传感器融合方法构建井下巷道的三维点云地图，有效实现未知环境的可视化呈现，并为凿岩机器人自主导航提供地图指导，基于点云地图实现导航避障，有效区分环境障碍，规划安全可通行路径，为凿岩机器人自主导航提供解决策略。本文的主要研究内容如下：

针对煤矿巷道特殊环境以及凿岩机器人的具体工况，分析凿岩机器人自主导航需求，完成凿岩机器人自主导航功能设计，提出基于激光雷达及惯性融合的自主导航策略。设计并搭建了移动机器人自主导航系统试验平台，对选用激光雷达及惯性传感器进行数据处理及标定，为后续地图构建和自主导航奠定基础。

针对巷道环境噪声点云过多，提取有效几何特征以去除冗余噪声并完成点云特征匹配。探究巷道点云的退化特性，针对退化环境状态估计不完备的问题，展开退化环境下点云特征匹配的鲁棒优化，提出基于退化检测及强度辅助的特征匹配方法。建立基于图优化的激光雷达-惯性传感器融合 SLAM 框架，由惯性里程计和激光惯性里程计两步优化过程组成，实现高精度、高鲁棒性的三维地图构建。

针对航迹推算定位积累误差严重、基于已知地图定位存在相似场景的歧义性等问题，展开已知地图约束的激光雷达-惯性传感器融合导航定位研究，以输出全局地图坐标系下的绝对坐标。针对机器人在障碍物约束下的路径规划，通过点云地面分割以保障机器人区分空间内的障碍物及可通行区域，通过三次样条曲线输出曲率连续的避障路径。

在自主导航试验平台上进行了地图构建及自主导航试验，在地下车库一类封闭环境中，地图构建的点云地图误差 0.04m，里程计误差 0.017m；导航误差 0.09m。在地下巷道退化环境中，地图构建的点云地图误差 0.06m，里程计误差 0.030m；导航误差 0.12m。在凿岩机器人上进行了 SLAM 试验，改进 SLAM 方法即使是在凿岩机器人剧烈振动、环境条件恶劣的情况下仍然具有较高适用性，SLAM 的里程计误差 0.031m。试验结果表明，论文所提方法能够提供较高精度的环境地图并完成自主导航，为实现巷道掘进装备自主导航提供了理论参考。

论文共有图 71 幅，表 14 个，引用格式 108 篇。

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图 5-4 地下车库定位试验环境

Figure 5-4 Experimental environment of localization in underground garage

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本试验采用 Nokov 红外动作捕捉系统获取移动机器人的运动轨迹，其定位误差在亚毫米级，可以看作是连续真实轨迹。图 5-4 是该试验环境。

引用格式 吕振礼.巷道凿岩机器人地图构建及自主导航技术研究[D].中国矿业大学，2023.DOI：10.27623/d.cnki.gzkyu.2023.002313.

链接

https://kns.cnki.net/kcms2/article/abstract?v=DFdco8SIy0IP4DTj0fF0XTgmHScc8F-NNiE65-ZXzr8xvpR9gbFJqybUoNOTavMFBwkgzhuUfYrUQ7gzu_0wc6L3AnPmZCO3EAlx4ZRZQ68UBb79Rt3ZOw==&uniplatform=NZKPT&language=gb

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基于安全强化学习的多无人机编队与避障控制

关键词

安全强化学习；多无人机系统；编队控制；控制障碍函数；未知环境

摘要

多无人机编队作为无人机技术的重要发展方向,展现出强大的应用潜力和研究价值.近年来,基于深度强化学习算法训练多无人机编队控制策略得到了愈发广泛的关注.然而,在编队策略学习中,环境的未知性和传感器误差等因素可能导致无人机采取不安全或不合理的动作,影响策略学习的安全性和稳定性.针对这一问题,提出了一种基于安全强化学习的多无人机编队与避障控制方法.首先,考虑环境扰动、传感器误差等因素的影响,基于部分观测马尔可夫(Markov)决策过程建立多无人机编队控制模型.在此基础上,设计最大池化多智能体深度确定性策略梯度算法,训练编队控制的标称策略;同时构建基于控制障碍函数的安全过滤器,用于修正标称策略输出的不安全动作,确保编队飞行过程的安全性.最后,通过数值仿真和实物飞行实验,验证了所提多无人机编队避障方法的安全性和有效性.

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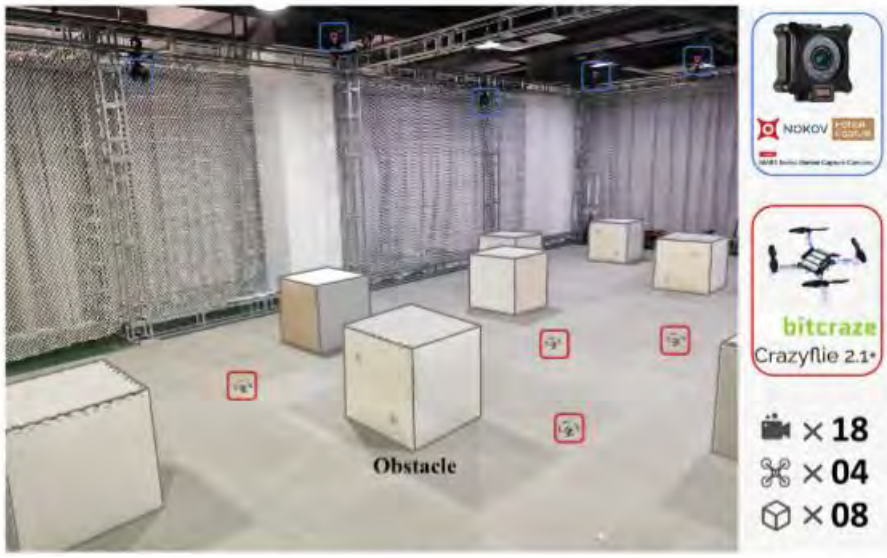

图 8 (网络版彩图) 实物飞行实验系统.

Figure 8 (Color online) Real-world experiment system.

NOKOV 度量动作捕捉在研究中的应用摘录

为验证所提编队避障算法在实际飞行中的有效性和可靠性，进行了实物飞行实验。实验系统配置如图 8 所示，使用 4 架 Crazyflie 无人机 \[39] 作为实验对象，以评估所提编队避障算法的性能。NOKOV 度量光学三维动作捕捉设备通过追踪无人机上的感光球实时更新各架无人机的速度位置信息。在装有 Ubuntu20.04 系统的电脑上部署编队避障控制算法，为模拟无人机在未知环境下的飞行情况，编写一个感知模块，即无人机仅有在其感知半径内才能与邻居无人机进行通信以及观测到障碍物。在每一控制周期内，根据 NOKOV 动捕设备反馈的各架无人机的状态信息，组合系统联合观测信息输入到强化学习网络中，并通过 Crazyradio 2.0 以 20 Hz 的控制频率为各架无人机发布动作指令。

引用格式 陈众楷,周晗,孙懿豪,等.基于安全强化学习的多无人机编队与避障控制[J].中国科学:信息科学,2026,56(02):409-424.

链接

https://kns.cnki.net/kcms2/article/abstract?v=H8HwaL3t0AuUQ1xk3vylBn1T7j1fskvZgJBv7Say7uo4JNb2obgF4FlGL5v3jfWRbUKYdQbwBqIli3SfQgqzRV2S-T7d9hQwQVpD_gnKrIdiKu-EC1UBwK2GnHLTQ40fCa4YteMfsmlyXarHPH7494CQr5IJp06bHmDnJzYT0_Hgbu5L7SaMrQ==&uniplatform=NZKPT&language=CHS

基于故障风险学习的无人机安全控制方法

关键词

故障风险; 条件在险价值; 风险量化与学习; 风险倾向;安全控制;

摘要

针对无人机在受到故障风险影响时其安全运动能力可能显著退化的问题,提出了基于故障风险量化与学习的自适应安全控制方法.首先,在固定时间故障观测设计基础上利用条件在险价值(conditional value-at-risk,CVaR)对故障风险进行量化评估,采集真实实验数据分析不同故障风险水平下无人机自身位置不确定性分布,实现对故障风险状态的显式感知和尾部风险事件的有效捕捉.其次,结合滑动时间窗与轻量化反向传播神经网络学习故障风险对位置不确定性的影响,实现对故障风险的快速感知与响应.进一步地,采用自适应风险倾向控制补偿策略,实现控制策略的平滑调整与自适应安全控制.实验结果表明,相比于整体式滑模控制方法,所设计的自适应控制策略在保证轻量化算力的前提下,能够提升不同故障水平下控制器响应速度与轨迹跟踪精度.

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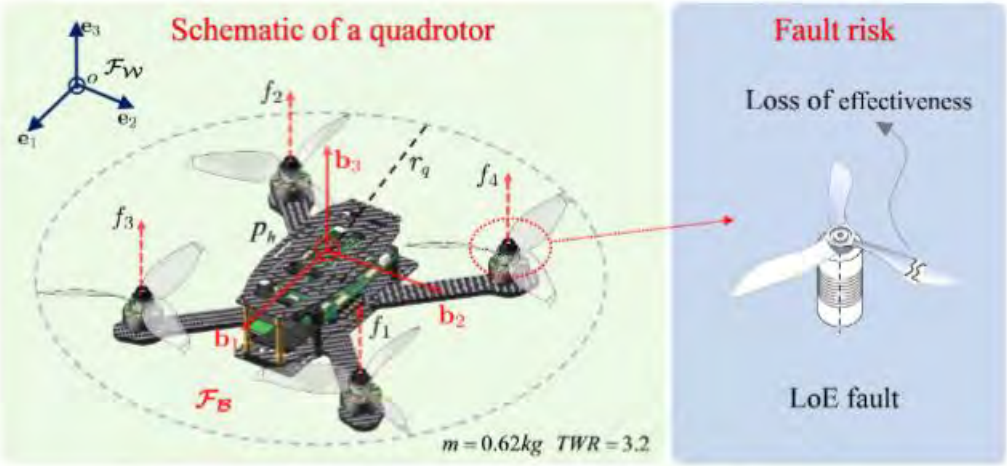

图 1 (网络版彩图) 四旋翼无人机和故障风险示意图.

Figure 1 (Color online) Schematic of a quadrotor UAV and the LoE fault risk.

NOKOV 度量动作捕捉在研究中的应用摘录

> *3.3 基于风险学习的自适应安全控制方法*
> *故障风险对位置不确定性的影响通常具有滞后性与累积性，直接用单时刻输入建模容易忽略这种历史信息依赖。因此，本节设计了一种结合滑动时间窗与轻量化的反向传播神经网络的学习框架，用于模拟在多时间步故障状态演化下，对位置不确定性分布导致的风险量化值的变化规律建模。设当前时间为 kk，则在 TwTw 个时间步内的模型输入的维度特征包括电机能力系数序列 γi(k−t)γi (k−t)、故障风险置信度序列 αf(k−t)αf (k−t) 和无人机速度序列 V(k−t)V(k−t)，其中 t=0,1,…,Tw−1t=0,1,…,Tw −1。其中，电机能力系数由固定时间故障观测器估计得到，置信度是对风险的容忍程度人为给定，无人机飞行速度通过动作捕捉系统 **NOKOV**量测得到。*

引用格式 卞俊,章健淳,杨彬,等.基于故障风险学习的无人机安全控制方法[J/OL].中国科学:信息科学,1-14.https://link.cnki.net/urlid/11.5846.TP.20260424.1402.002.

链接

https://kns.cnki.net/kcms2/article/abstract?v=H8HwaL3t0AsJOTaI_qjCf7lgc8_M1nQsXZm0YuDcOGwrK5z7fABfxxTQkkokVjaMJqsC3LY02ACWm8TCXeqMzRLLNYHQcps00Gff2KhiFYR1HTs-dTKvkVarcYfo2NjTfHRE6m7awe-DBnYXRthGVqgNeZIGI5P3QY1rtjgJDx9LuJlqyaWupQ==&uniplatform=NZKPT&language=CHS

面向未知动态环境的多智能体分布式覆盖与避障协同控制算法

关键词

多智能体系统;覆盖控制;强化学习;模型预测控制;避撞;

摘要

针对未知动态环境下多智能体系统的快速搜索场景，本文提出了一种融合强化学习与模型预测控制的一体化分布式控制架构，旨在使集群在时变障碍、不完整先验地图与有限机载感知能力的约束下实现安全且高效的覆盖任务.传统基于模型的覆盖控制器往往依赖于精确的环境模型，而强化学习策略在面对未知的动态障碍物时可能产生危险指令.为解决上述问题，本文首先采用多智能体深度确定性策略梯度算法学习集群的协同覆盖策略，并输出智能体的覆盖控制量；其次，引入结合控制障碍函数的模型预测控制器，对覆盖控制量进行优化使其满足安全约束；最后，设计动态权重融合机制，实现智能体在全域扫描、动态避障、应急制动三种模式的自适应切换，以平衡集群的覆盖效率与安全保障.实验结果表明，所提算法在覆盖率和避撞成功率方面均优于现有基线算法，进一步地，半实物仿真实验也验证了该方法在真实场景中的可行性与扩展性.

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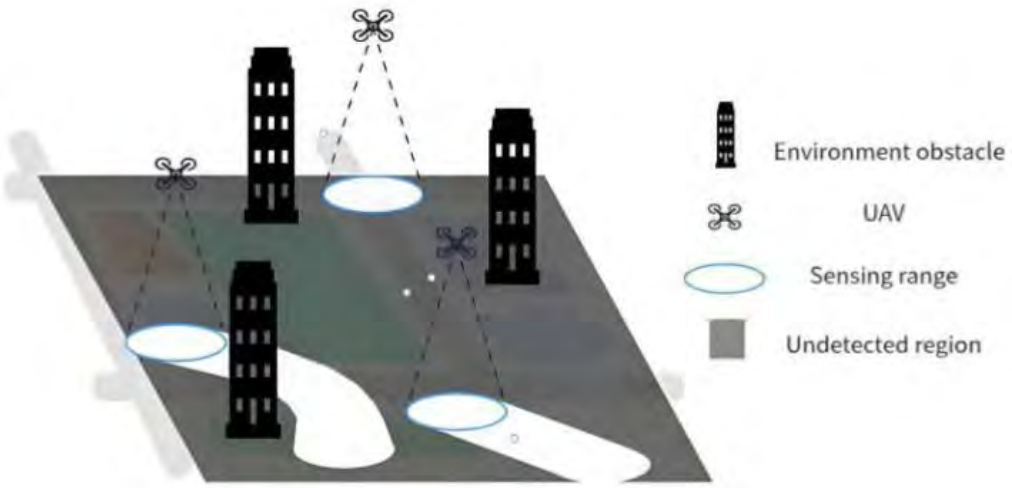

图 1　多无人机协同区域覆盖搜索场景.
Fig. 1　Multi-UAV cooperative area coverage search scenario.

NOKOV 度量动作捕捉在研究中的应用摘录

> *3.3 半实物实验验证\n 为验证算法在真实系统中的适用性，构建了以 NOKOV 光学动捕系统为核心的半实物验证平台，该系统由 12 台红外相机组成，可为无人机提供毫米级高精度位姿反馈。半实物实验在 4 m×6 m 的模拟城市沙盘环境中进行，使用四架 Crazyflie2.1 小型无人机进行算法验证，其中三架无人机执行覆盖任务，配备 Multi-ranger deck 红外测距模块，支持局部感知与辅助避撞，一架无人机模拟动态障碍物，其中安全距离阈值定义为 d_{safe}=0.09m。当无人机与障碍物距离小于激光雷达探测范围时，系统将激活动态避障控制机制。若距离进一步小于安全阈值，即判定为碰撞。详细物理参数见表 3。*

引用格式 石磊,吕建鹏,麻壮壮,等.面向未知动态环境的多智能体分布式覆盖与避障协同控制算法[J].工程科学学报,2026,48(7):1528-1539.DOI:10.13374/j.issn2095-9389.2025.10.09.001.

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https://kns.cnki.net/kcms2/article/abstract?v=sFGZ-GfRoEV1Lkxr8EqmFFxZpEAdl_BCAjKHvy71zQ2Va0yRQEua4LLILvmRn-qsfe8MIxBm3jINNdKO7d0DdkwYsGI-aAa4R9IztZ0EIEOrpavd1TQbMF5P4HhXcAzHEvVsbdMfWqYCYuzMBiCjJ5S5IyRhHceIo6fLAdnkNFVFQDv31s1QEg==&uniplatform=NZKPT&language=CHS

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II. Bionic Robot

A Bionics-Based Recovery Strategy for Micro Air Vehicles

Keywords

Aerial robots, motion control, recovery strategy

Abstract

Micro air vehicles' (MAVs) movements can be significantly affected by physical contact with unknown moving objects (UMOs) from a random direction. To address this problem, low-latency sensors (cameras or radars) and high-speed processors are installed in six directions of aerial vehicles. However, this method is limited by hardware costs, load, and energy. In this article, a fast recovery strategy for MAVs is proposed, which is inspired by the recovery manoeuvre of mosquitoes hit by raindrops. When hit by falling raindrops, mosquitoes will descend along the falling direction of raindrops to gradually counteract the kinetic energy of the impact induced by the raindrops. During the descent, mosquitoes will gradually tilt to one side but move in the opposite direction, and finally deviate from the falling route of raindrops. To simulate the recovery strategy, a micro aerial robot called RobMos is designed. The RobMos is an overactuated system that can decouple the position control from the attitude control. Using the recovery strategy, the robot can quickly recover to a stable attitude after being impacted by UMOs. An onboard inertial measurement unit is used to estimate the impact location. Finally, the prototype can bear the impact of objects that are two times its own weight. Moreover, the generalizability of this strategy is also discussed, and it is proved that the RobMos can even recover attitude after being hit by the UMO in a lateral direction.

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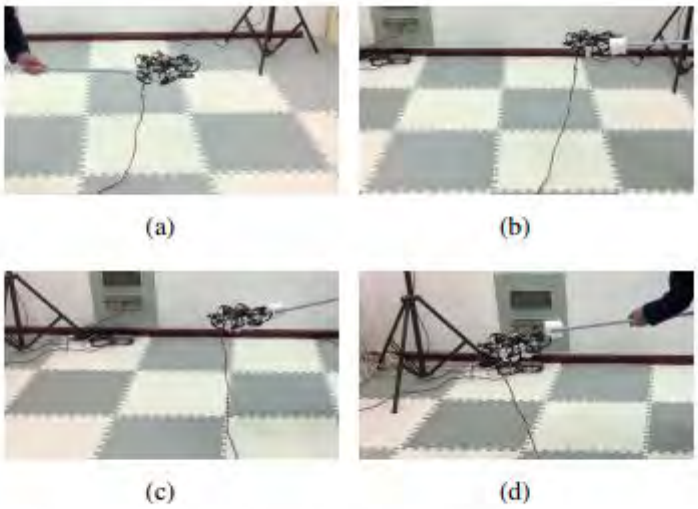

Fig. 13. Sequence of an recovery control maneuver.

How NOKOV Contributes to the Research

An NOKOV Mars-1.3H motion-capture system is used tomeasure the six-DoF pose data of the flying robot in an indoorenvironment. The ground station is a computer using Intel i7processor, which is connected to the motion capture systemthrough a network cable.

Citation Li B, Liu K, Ma L, et al. A Bionics-Based Recovery Strategy for Micro Air Vehicles[J]. IEEE Transactions on Industrial Electronics, 2022, 70(6): 6068-6077.

Link https://ieeexplore.ieee.org/abstract/document/9841434

A Directional Locomotion Control of Cyborg Locusts for Complex Outdoor Environments

Keywords

Cyborg locusts, Turning and jumping control, Directional locomotion, Search and rescue

Abstract

The ability of cyborg locusts to achieve directional movement in complex outdoor environments is critical for search and rescue missions. Currently, there is a lack of research on motion control for cyborg locusts in outdoor settings. In this study, we developed cyborg locusts capable of performing directional locomotion in intricate outdoor environments, including jumping over obstacles, climbing slopes, traversing narrow pipelines, and accurately reaching predetermined targets along specified routes. We designed a miniature electrical backpack (10 mm × 10 mm, 0.75 g) capable of receiving stimulus parameters (frequency, duty ratio, and stimulation time) via Bluetooth commands from mobile phones. Electrical stimulation of locust sensory organs, such as the antennae and cercus, induced turning and jumping behaviors. Experimental testing of locust movement control was conducted under outdoor conditions with a short electrical stimulation interval. Results showed a positive correlation between locust turning angles and electrical stimulation parameters within a specified range, with an average jumping height exceeding 10 cm. Additionally, the success rate of locust turning and jumping behaviors correlated positively with the interval time between electrical stimulations. Adjusting these intervals during forward crawling phases increased the likelihood of the locusts jumping again. In conclusion, this study successfully achieved directional locomotion control of cyborg locusts outdoors, providing insights and Citation for advancing search and rescue capabilities.

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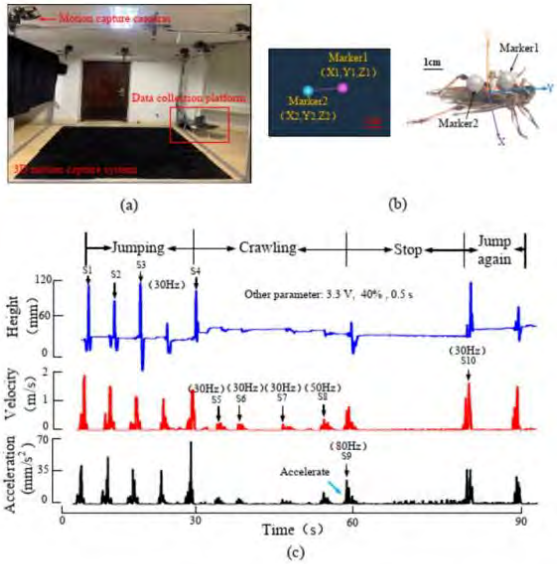

Fig. 8 Indoor jumping and crawling test of cyborg locust. **a** Overview of the 3D motion capture system. **b** A live locust with an electrical backpack, marked on the notum and abdomen. **c** Height, velocity, and acceleration data collected by the 3D motion capture system during locust jumping or crawling

How NOKOV Contributes to the Research

Jumping and crawling are the primary methods of movement for locusts to move forward. We recorded the jumping and crawling of cyborg locusts using a 3D motion capture system (NOKOV, with 7 motion capture cameras), as illustrated in Fig. 8a. The cyborg locusts had marker points (Marker 1 and Marker 2) attached, which could be recognized by the system for evaluating height, velocity, and acceleration (Fig. 8b). Initially, we sent electrical stimulation parameters (3.3 V, 30 Hz, 40%, and 0.5 s) to the cyborg locusts every 5 s to induce jumping.

Citation Huang X, Li T, Sun K, et al. A Directional Locomotion Control of Cyborg Locusts for Complex Outdoor Environments[J]. Journal of Bionic Engineering, 2025, 22(2): 596-607.

Link https://link.springer.com/article/10.1007/s42235-024-00639-8

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A HUG taxonomy of humans with potential in human–robot hugs

Abstract

Humans can easily perform various types of hugs in human contact and affection experience. With the prevalence of robots in social applications, they would be expected to possess the capability of hugs as humans do. However, it is still not an easy task for robots, considering the complex force and spatial constraints of robot hugs. In this work, we propose the HUG taxonomy, which distinguishes between different hugging patterns based on human demonstrations and prior knowledge. In this taxonomy, hugs are arranged according to (1) hugging tightness, (2) hugging style, and (3) bilateral coordination, resulting in 16 different hug types. We then further study the hug type preference of humans in different scenarios and roles. Furthermore, we propose a rule-based classification system to validate the potential of this taxonomy in human–robot hugs based on a humanoid robot with an E-skin of contact sensation. The HUG taxonomy could provide human hugging behavior information in advance, facilitating the action control of humanoid robots. We believe the results of our work can benefit future studies on human–robot hugging interactions.

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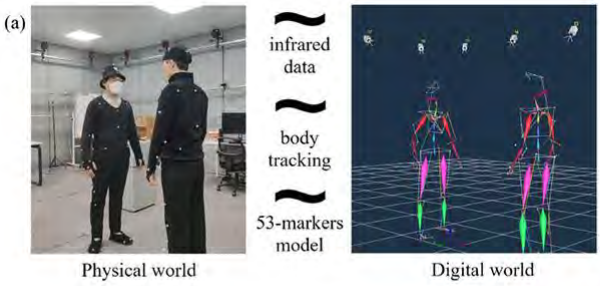

(b)

Participant ID	Gender	Height	Ages
1	Female	1.61m	25
2	Male	1.73m	27
3	Male	1.69m	31
4	Male	1.86m	28
5	Male	1.79m	25
6	Male	1.76m	27

Figure 2. Motion capture experiments of the human demonstration. (**a**) Motion capture system. (**b**) Participant information.

How NOKOV Contributes to the Research

As shown in Fig. 2a, we utilize the motion capture system from NOKOV to collect data. It consists of 20 infrared cameras with 60fps, arranged in a square on the ceiling of a 6.5m×6.5m×2.5m quiet room, with five cameras on each side. Combined with the 53-marker human body detection and modeling algorithms, human demonstrations can be transformed into digital models, making physical properties more apparent.

Citation Yan, Z., Wang, Z., Ren, R. et al. A HUG taxonomy of humans with potential in human–robot hugs. Sci Rep 14, 14212 (2024). https://doi.org/10.1038/s41598-024-64825-8

Link https://www.nature.com/articles/s41598-024-64825-8

A Lightweight Powered Knee Prosthesis Replicating Early-Stance Knee Flexion During Level Walking

Keywords

Prosthetics and exoskeletons, actuation and joint mechanisms

Abstract

Powered knee prostheses promise to improve the mobility of transfemoral amputees by imitating the biomechanics of the missing knee joint. Unfortunately, the heavy weight and short battery life severely limit the application of powered prostheses. Here, we present a lightweight powered knee prosthesis, which employs a series elastic actuator (SEA) integrating a high torque density external rotor motor, a ball screw and a slider-crank mechanism. A genetic algorithm (GA) is used to optimize the slider-crank mechanism's key parameters and improve the prosthesis's compactness. Combined with the hardware, a hybrid controller is proposed, which comprises impedance control in the stance phase with position control during the pre-swing and swing phases. The controller was applied to the powered prosthesis, and its capability to provide level walking functionality was evaluated on four above-knee amputees. The data obtained from these experimental trials indicated that the prosthesis could replicate the key biomechanical functions of a biological knee in the sagittal plane while the weight was lighter than most powered knee prostheses. In addition, the vertical ground reaction force (GRF) was quantitatively analyzed to validate that the powered knee prosthesis could improve wearing comfort with early-stance knee flexion.

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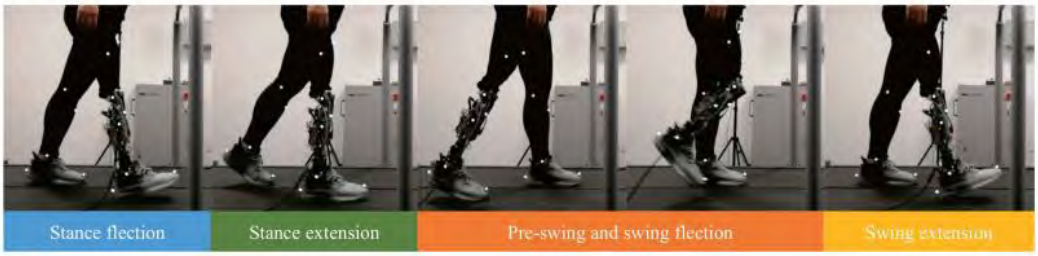

Fig. 11. Test of level-ground walking.

How NOKOV Contributes to the Research

To collect gait data from the subjects, we utilized an 8-camera motion capture system (NOKOV Seeker, China)and Bertec force plates to measure the GRF data, including the position ofthe center of pressure (COP).The subject was marked using the approach described in.

Citation Chen W, Ma Y, Ren L, et al. A lightweight powered knee prosthesis replicating early-stance knee flexion during level walking[J]. IEEE Robotics and Automation Letters, 2024, 9(11): 9693-9700.

Link https://ieeexplore.ieee.org/document/10564154

A wireless image and sound sensing cyborg locust based on electrical stimulation

Keywords

Cyborg Locust, Sensory Electrical Stimulation, Directional Movement, Image and Sound Sensing, Search and Resc

Abstract

In this paper, a cyborg locust based on electrical stimulation for image and sound sensing has been proposed. The PC control terminal sent electrical stimulation instructions to a micro electronic backpack through wireless Bluetooth to induce locust directional movement. The cyborg locust could jump or bypass obstacles in complex environments and move in a targeted direction to the target location, and maintained body righting after landing, while collecting image and sound information of the environment. The turning and jumping behavior in locusts could be induced through electrical stimulation of their sensory organs, such as antennae and cercus. The micro electronic backpack has electrical stimulation function, image and sound sensing function. The designed cyborg locust was suitable for directional movement in complex and narrow environments, and collected clear and distinguishable image and sound information, such as search and rescue.

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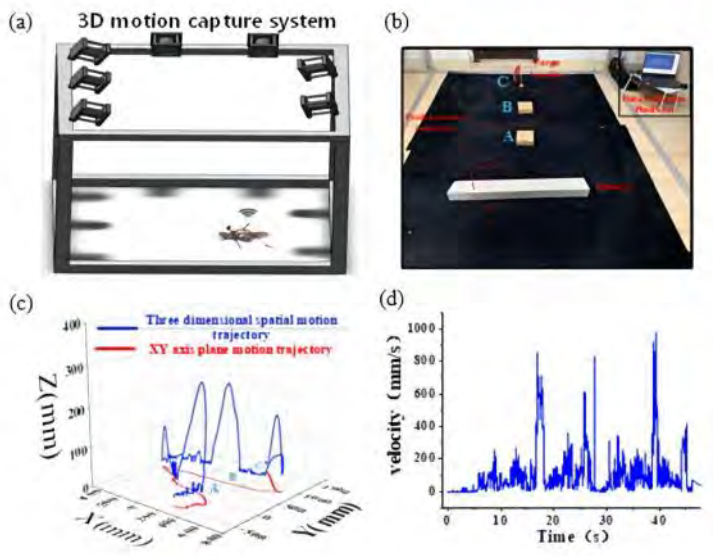

Figure 6: Cyborg locust directional motion test. (a) The 3D motion capture system can collect three-dimensional position and velocity information. (b) The cyborg locust has a directional movement route, first jumping over obstacles, then bypassing obstacles A and B, and finally reaching the target location C. (c) The motion trajectory of cyborg locusts in three-dimensional space and their projected trajectory on the XY plane. (d) The speed variation of cyborg locust's directional movement.

How NOKOV Contributes to the Research

Firstly, we conducted directional motion testing of cyborg locustsusing an indoor 3D motion capture system (NOKOV) (Figure. 6(a)).NOKOV Motion Capture system is a high-performance device usedto accurately capture and collect motion data of moving objectsin three-dimensional space.

Citation Huang X, Li T, Yang B. A wireless image and sound sensing cyborg locust based on electrical stimulation[C]//Proceedings of the 2024 International Conference on Innovation in Artificial Intelligence. 2024: 148-153.

Link https://dl.acm.org/doi/10.1145/3655497.3655527

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An Image Uncertainty Calibration Network for Robotic Clothes Grasping

Keywords

Robotic Clothes Grasping, Robot Perception, Data Synthesis, Computer Vision

Abstract

Labeled synthetic data generated by physics engines are commonly combined with real data for grasp point prediction in robotic clothes manipulation tasks. However, domain adaptation from synthetic to real data remains challenging due to two major sources of uncertainty: (1) visual discrepancies between synthetic and real images, and (2) inconsistencies in label scales or units. To address these issues, we propose an Uncertainty Calibration Network (UCN), which employs fine-grained feature learning and difference calibration to reduce the domain gap in image appearance. To handle label uncertainty, UCN is trained in an unsupervised manner without using synthetic labels, enabling synthetic images to enrich feature diversity and improve domain-shared representations. This approach significantly enhances the model's generalization ability across domains, achieving robotic grasping and unfolding success rates of 84% and 75% in the real world, respectively.

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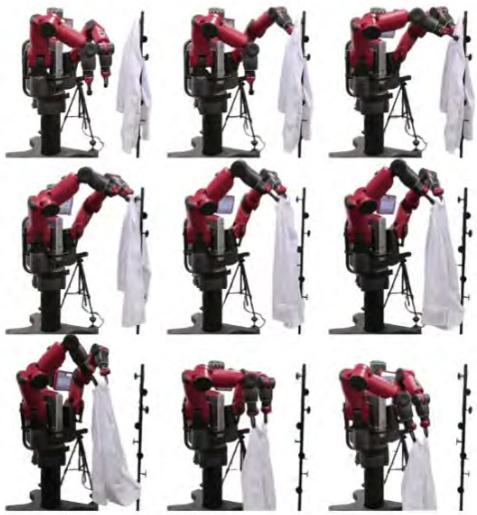

Fig. 1. A sequential illustration of the clothes grasping and unfolding process: the proposed Uncertainty Calibration Network (**UCN**) predicts uncertainty-calibrated grasping points; the Baxter robot plans and executes the grasp, then moves the clothes to the target location for unfolding.

How NOKOV Contributes to the Research

3 Preliminary
3.1 Data Acquisition
We constructed a clothes grasping dataset using both real and synthetic data.Real Data. As shown in Fig.2, the Baxter robot interacted with clothes hung on a hanger, while a Kinect v2 camera captured depth images from a fixed position. Grasping points were marked on both shoulders of the clothes, and their 3D coordinates were recorded using the Nokov Motion Capture System.We collected 5,000 real samples by repeatedly re-hanging clothes under varying conditions, with segmentation performed using a 120160 cm depth threshold.

Citation Wang X, Tu Z, Gao Y. An Image Uncertainty Calibration Network for Robotic Clothes Grasping[C]//Chinese Intelligent Automation Conference. Singapore: Springer Nature Singapore, 2025: 212-222.

Link https://link.springer.com/chapter/10.1007/978-981-95-4053-2_23

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Bio-inspired Design and Inverse Kinematics Solution of an Omnidirectional Humanoid Robotic Arm with Geometric and Load Capacity Constraints

Keywords

Humanoid robotic arm, Bio-inspired design, Inverse kinematics solution, Load capacity constraint, Geometric constraint

Abstract

Inspired by the driving muscles of the human arm, a 4-Degree of Freedom (DOF) concentrated driving humanoid robotic arm is proposed based on a spatial double parallel four-bar mechanism. The four-bar mechanism design reduces the inertia of the elbow-driving unit and the torque by 76.65% and 57.81%, respectively. Mimicking the human pose regulation strategy that the human arm picks up a heavy object by adjusting its posture naturally without complicated control, the robotic arm features an integrated position-level closed-form inverse solution method considering both geometric and load capacity limitations. This method consists of a geometric constraint model incorporating the arm angle (φ) and the Global Configuration (GC) to avoid joint limits and singularities, and a load capacity model to constrain the feasible domain of the arm angle. Further, trajectory tracking simulations and experiments are conducted to validate the feasibility of the proposed inverse solution method. The simulated maximum output torque, maximum output power and total energy consumption of the robotic arm are reduced by up to 2.0%, 13.3%, and 33.3%, respectively. The experimental results demonstrate that the robotic arm can bear heavy loads in a human-like posture, effectively reducing the maximum output torque and energy consumption of the robotic arm by 1.83% and 5.03%, respectively, while avoiding joints beyond geometric and load capacity limitations. The proposed design provides a high payload–weight ratio and an efficient pose control solution for robotic arms, which can potentially broaden the application spectrum of humanoid robots.

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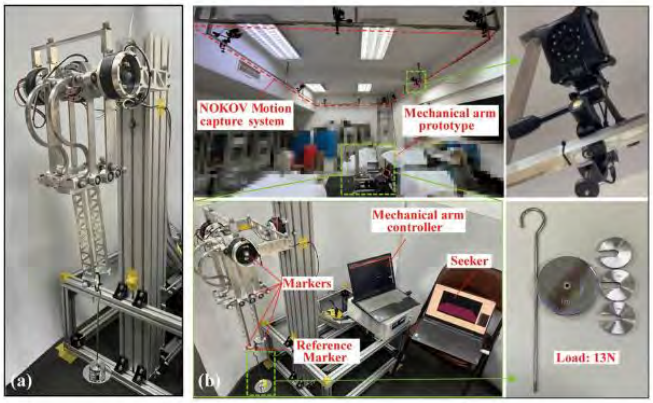
Fig. 21 **a** Robotic arm prototype. **b** Hardware equipment for trajectory tracking



How NOKOV Contributes to the Research

Figure 21a depicts the physical prototype of the robotic arm. In Fig. 21b, the NOKOV motion capture system is utilized to capture the trajectory of the robotic arm's end. The soft-ware Seeker is used for data acquisition. A 13-N weight is suspended at the end of the robotic arm as the load. The joint trajectories (Θ1(t) and Θ2(t)) input to the motors are the same as the simulation input, as shown in Fig. 21. The trajectory tracking prototype experiment is repeated three times, and the average motor torque and joint position output from the three experiments are analyzed.

Citation Zhu Z, Luo Z, Zhu Y, et al. Bio-inspired Design and Inverse Kinematics Solution of an Omnidirectional Humanoid Robotic Arm with Geometric and Load Capacity Constraints[J]. Journal of Bionic Engineering, 2024, 21(2): 778-802.

Link https://link.springer.com/article/10.1007/s42235-023-00475-2

CBMC-V2: A CNS-inspired Framework for Real-time Robotic Arm Control

Keywords

Spinal cord, Neuromorphics, Trajectory tracking, Humanoid robots, Manipulators, Robot sensing systems, Motors, Real-time systems, Robustness, Frequency control

Abstract

In recent years, bio-inspired control algorithms for robotic arms have garnered significant attention due to their remarkable adaptability. In this paper, we introduce a real-time framework on the basis of CBMC [13], to control a 7-DOF robotic arm using neuromorphic chip. Our proposed framework comprises five modules: the cerebral sensory cortex module, the cerebral motor cortex module, the cerebellum module, the brainstem module, and the spinal cord module. These modules operate within a hierarchical structure consisting of three control loops, each running at different frequencies. The effectiveness of our approach is validated through trajectory tracking control tasks in simulation. Subsequently, we deploy the algorithm on a neuromorphic chip to test its performance on a robotic arm platform. The experimental results clearly demonstrate the superior control effectiveness and robustness of our methodology than the previous version in complex tasks.

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How NOKOV Contributes to the Research

The human hand position and orientation are captured by the NOKOV motion capture system, and converted to joint trajectories for the algorithm to track.

Citation Pang Y, Li Q, Wang Y, et al. CBMC-V2: A CNS-inspired Framework for Real-time Robotic Arm Control[C]//2024 IEEE-RAS 23rd International Conference on Humanoid Robots (Humanoids). IEEE, 2024: 121-128.

Link https://ieeexplore.ieee.org/document/10769842

Continuous adaptive gaits manipulation for three-fingered robotic hands via bioinspired fingertip contact events

Abstract

The remarkable skill of changing its grasp status and relocating its fingers to perform continuous in-hand manipulation is essential for a multifingered anthropomorphic hand. A commonly utilized method of manipulation involves a series of basic movements executed by a high-level controller. However, it remains unclear how these primitives evolve into sophisticated finger gaits during manipulation. Here, we propose an adaptive finger gait-based manipulation method that offers real-time regulation by dynamically changing the primitive interval to ensure the force/moment balance of the object. Successful manipulation relies on contact events that act as triggers for real-time online replanning of multifinger manipulation. We identify four basic motion primitives of finger gaits and create a heuristic finger gait that enables the continuous object rotation of a round cup. Our experimental results verify the effectiveness of the proposed method. Despite the constant breaking and reengaging of contact between the fingers and the object during manipulation, the robotic hand can reliably manipulate the object without failure. Even when the object is subjected to interfering forces, the proposed method demonstrates robustness in managing interference. This work has great potential for application to the dexterous operation of anthropomorphic multifingered hands.

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Fig. 1. Location of markers.

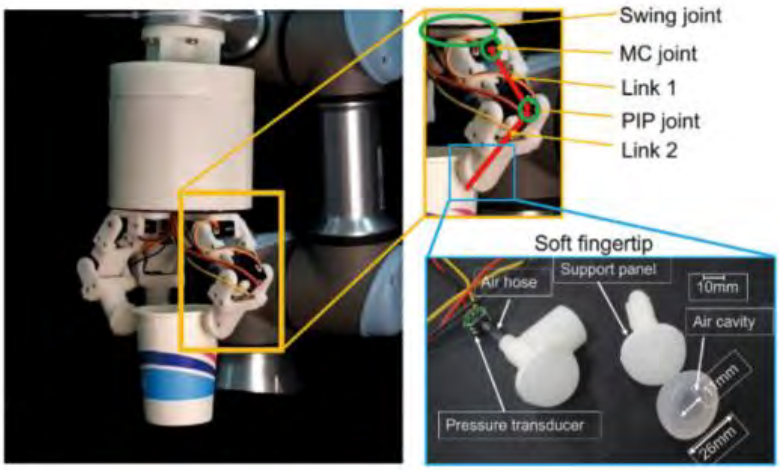

Fig. 4. Three-fingered robotic hand prototype and soft fingertip with embedded sensor.

How NOKOV Contributes to the Research

The posture parameters of the object are sampled and calculated using the NOKOV optical 3D motion capture system.. The NOKOV optical 3D motion capture system estimates the object's angular velocity during manipulation.

Citation Xiaolong Ma, Jianhua Zhang, Binrui Wang, Jincheng Huang, Guanjun Bao, Continuous adaptive gaits manipulation for three-fingered robotic hands via bioinspired fingertip contact events,Biomimetic Intelligence and Robotics,Volume 4, Issue 1,2024,100144

Link https://www.sciencedirect.com/science/article/pii/S2667379724000020

D2MFusion: An End-to-End Differentiable Trajectory Optimizer for Safe Reactive Navigation

Keywords

Safe reactive navigation, end-to-end differentiable trajectory optimizer, planning and learning

Abstract

Data-driven methods provide effective solutions for robot trajectory generation in dynamic environments. Many physical constraints exist in the real world, and understanding these constraints to generate feasible trajectories for kinematics or dynamics is highly demanding regarding the data quantity. Due to the black box, it is also challenging to ensure the safety of the trajectories planned by data-driven models. In this letter, we propose an end-to-end model (D2MFusion) that fuses data-driven components and a model-based optimizer. D2MFusion uses a differentiable optimization layer (dLQR) that forms a backpropagation loop with a perception network. With the input BEV image, the perception network outputs the environmental feature vector to adjust the optimizer parameters to adapt to the dynamic environment. We train this fusion planner to imitate expert trajectories on a real self-driving dataset and demonstrate the planner's explainability, data efficiency, and safe reactivity through closed-loop simulations. We also conduct experiments on a Unitree Go2 in three different scenarios to demonstrate the ability of our method to navigate in dynamic environments.

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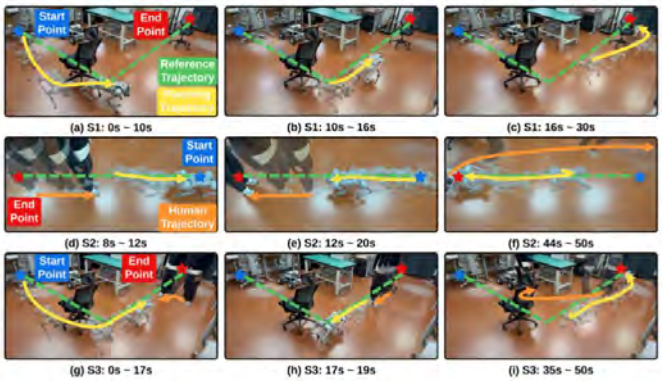

Fig. 5. **Video snapshots of our method in three real-world experiments.** Scenario I in which Go2 bypasses two obstacles that appear on the reference trajectory to reach the endpoint safely is illustrated from (a) to (c). Go2 interacts with the human and always maintains a safe distance, as shown in (d)~(f). In Scenario III, Go2 bypasses the first obstacle and then interacts safely with the human who suddenly appears, and finally bypasses the second obstacle to reach the endpoint as shown in (g)~(i).

How NOKOV Contributes to the Research

Implementation: We use ROS2 for control and sensor communication. Expert trajectories are collected by manually operating the Go2 with a joystick in the testing environment, including five obstacle avoidance trajectories (732 points) and three human interaction trajectories (539 points). The dataset contains robot and obstacle states (position, orientation, velocity) captured by the NOKOV motion capture system at 10 Hz. Training is performed on an NVIDIA RTX4060 (8 GB). During both training and experiments, the input BEV representation has four channels, excluding the lane and road layers used in the simulation. Each BEV layer is generated from motion capture data and transformed into the Go2 coordinate frame, consistent with the simulation setup. The BEV covers 2.5 m × 2.5 m with a resolution of 0.05 m. The planned trajectory from D2MFusion is executed by Go2 through its low-level tracking controller. Data processing and trajectory planning run on a computer with an Intel Core i9-13900HX CPU and 32GB RAM. The planner operates at 10 Hz with a 2 s horizon, identical to the simulation setting. Fig. 5 illustrates the start and end points (blue and red stars), the reference trajectory (green dashed line), the trajectory planned by D2MFusion (yellow arrows), and the human trajectory (orange arrows).

Citation Zhou X, Zhang S, Li X. D2MFusion: An End-to-End Differentiable Trajectory Optimizer for Safe Reactive Navigation[J]. IEEE Robotics and Automation Letters, 2025.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001579024200003

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Design of a hover-capable flapping wing micro air vehicle with abdomen-wing coupled control

Keywords

Flapping wing; Micro air vehicles; Hover-capable; Flight control; Gimbal test

Abstract

Insects and hummingbirds can achieve agile maneuvers through concomitant control of the abdomen and wings. However, hover-capable Flapping Wing Micro Air Vehicles (FWMAVs) inspired by insects and hummingbirds primarily rely on wing motion modulation, leading to insufficient control torques and poor maneuverability. To address this problem, we propose the BH-Fly, a hover-capable FWMAV with a novel abdomen-wing coupled control strategy. The BH-Fly weighs 32.5 g with a wingspan of 22 cm and can hover over 5 minutes with onboard batteries. The abdomen-wing coupled control is implemented through a linkage mechanism that synchronously rotates the abdomen and wing root. Experimental results show that this novel control strategy generates maximum pitch and roll torques of 6.3 N·mm and 7.8 N·mm, respectively, improving control torques by 26% and 56% over the existing hover-capable FWMAVs. Gimbal tests reveal that the BH-Fly achieves a maximum roll rate and angular acceleration of 35.48 rad/s and 175.47 rad/s^2, respectively. This enables the BH-Fly to complete a 360° turn in 0.18 s or about 4 flaps. Moreover, the dimensionless values of the maximum roll rate and angular acceleration match those of real hummingbirds. These findings demonstrate that the abdomen-wing coupled control provides a more biomimetic and efficient strategy for hover-capable FWMAVs.

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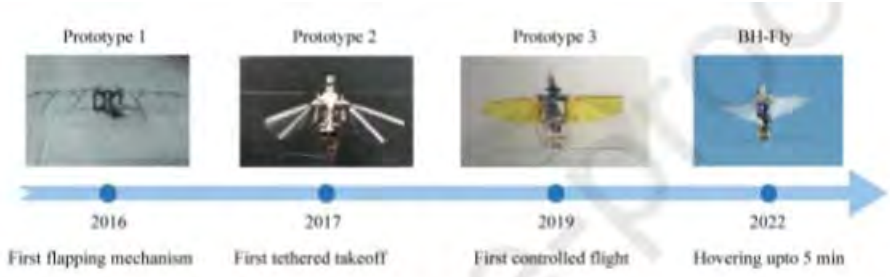

Fig. 1 Evolution of BH-Fly.

How NOKOV Contributes to the Research

6.2 Flight result
Free-flight tests were conducted after tuning control parameters on the gimbal systems. During these tests, the BH-Fly was powered by two 3.7 V 100 mA.h batteries in series, achieving a maximum flight duration of 5 minutes.As shown in Fig. 15(a), the BH-Fly carried four markers for motion capture, and its flight data was recorded by a motion capture system comprising 8 cameras(Mars4H NOKOV,180 FPS, accuracy 0.1 mm). Free-flight testswere conducted in the attitude stabilization mode. with the desired angles for roll, pitch, and yaw equal to 0°.

Citation Jianghao W U, CHENG C, ZHANG Y, et al. Design of a hover-capable flapping wing micro air vehicle with abdomen-wing coupled control[J]. Chinese Journal of Aeronautics, 2025: 103807.

Link https://www.sciencedirect.com/science/article/pii/S1000936125004133

Development of a Load-Bearing, Terrain-Adaptive Hexapod Robot With Chebyshev-Linkage Legs

Keywords

Chebyshev linkage | dynamic simulation | hexapod robots | load-bearing capacity | terrain adaptability

Abstract

This study introduces an exploratory design for a hexapod load-carrying robot, aiming to address challenges commonly associated with quadruped robots, including limited load capacity and high control complexity. By leveraging a Chebyshev linkage-based over constrained leg-foot architecture that combines high rigidity and low friction, along with a multi-drive system for lateral movement, we propose a robot with improved adaptability to diverse terrains, such as snow, sand, puddles, ice, and deserts. This versatility suggests potential applications in areas such as factory inspection, field reconnaissance and transport, and desert exploration. Using static and dynamic analyses, we evaluated the leg structure's stress distribution and motion requirements, employing simulations in Workbench and Adams to cross-validate our theoretical calculations. The development of a prototype and its subsequent testing under various environmental conditions aimed to demonstrate the design's practicality and the robot's operational capabilities in real-world settings. Although the findings indicate progress toward enhancing load-bearing capabilities and terrain adaptability with reduced control complexity, further research and development are necessary to fully realize the potential of such robotic systems in practical applications.

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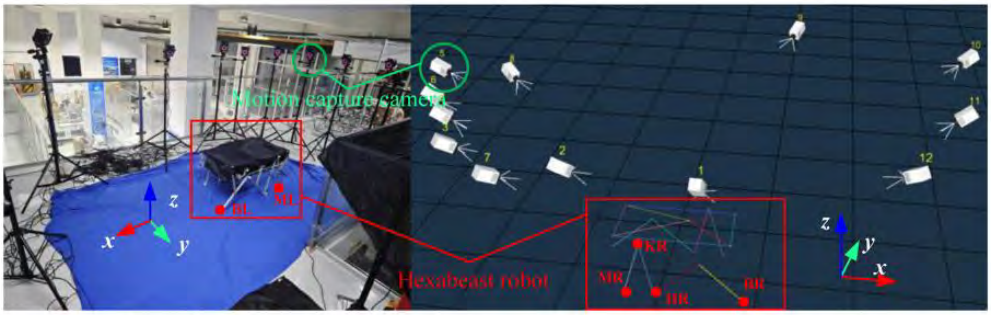

FIGURE 25 | Motion data validation of the Hexabeast robot. [Color figure can be viewed at wileyonlinelibrary.com]

How NOKOV Contributes to the Research

Motion Validation of the Hexabeast Robot - To verify the differences between the simulated and actual movements of the robot, we used the NOKOV Motion Capture System to capture the motion data of the Hexabeast robot. The specific testing environment is shown in Figure 25. As shown in Figure 25, a total of 12 capture cameras were used to collect the motion data. We randomly selected six points for validation, namely KR, MR, HR, BR, BL, and ML.

Citation Ju Z, Wu R, Guo D, et al. Development of a Load-Bearing, Terrain-Adaptive Hexapod Robot With Chebyshev-Linkage Legs[J]. Journal of Field Robotics, 2025, 42(4): 1439-1462.

Link https://onlinelibrary.wiley.com/doi/abs/10.1002/rob.22463

Development of Bioinspired Five-DOF Origami for Robotic Spine Assistive Exoskeleton

Keywords

Load lifting assistance, manual materials handling (MMH), origami, rigid-flexible coupled mechanism, robotic spine assistive exoskeleton, symmetric and asymmetric lifting

Abstract

Frequent and high-load manual material handling (MMH) tasks often cause back injuries to the workers, and back-support exoskeletons are developed for individuals with MMH tasks. However, these exoskeletons usually cannot adapt well to the movements of the wearer's spine. This article introduces a new bioinspired five degree of freedom (DOF) origami, and via mechanical design, a unique rigid-flexible coupled bioinspired origami mechanism is proposed. This origami mechanism is compact and lightweight, and it has stable kinematic behaviors. With the designed origami mechanisms, a novel active origami-based robotic spine assistive exoskeleton (OSAE) is developed to assist individuals with MMH tasks during the symmetric and asymmetric lifting. The OSAE is actuated by a cable-driven module through an underactuated spine module that consists of seven origami mechanisms. With the designed spine module, the OSAE can adapt well to the wearer's spine motions during MMH tasks. Modeling of the five-DOF origami is described, and an adaptive control strategy is proposed for the exoskeleton to adapt to different lifting methods and objects with different weights. The experimental results demonstrate the effectiveness of the proposed OSAE. During the symmetric lifting of a 10-kg object, a reduction of 41.28% of the average muscle activity of the wearer's lumbar erector spinae muscle (LES) is observed, and reductions of 30.15% and 39.54% of the average muscle activities of the wearer's left and right LES are observed, respectively, during the asymmetric lifting of a 10-kg object.

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Fig. 16. Experimental setup of the experiments.

How NOKOV Contributes to the Research

The experiments were conducted under an ethical approval that was reviewed and approved by the Research Committee of Hefei University of Technology, and the informed written consent from each participant was obtained before conducting the experiments. A motion capture system(NOKOV, Beijing Nokov Science & Technology Company Ltd.,China) with eight cameras was utilized to collect the 3-D motiondata of the participants' upper body.

Citation Chen B, Ni X, Zhou L, et al. Development of Bio-Inspired 5-DOF Origami for Robotic Spine Assistive Exoskeleton[J]. IEEE Transactions on Robotics, 2025.

Link https://ieeexplore.ieee.org/document/10989562

Emergence of Collective Behaviors for the Swarm Robotics Through Visual Attention-Based Selective Interaction

Keywords

Swarm robotics, probability and statistical methods, biologically-inspired robots

Abstract

Plenty of local interaction mechanisms have been proposed to achieve collective behaviors in swarm robotics. However, these mechanisms require robots to explicitly obtain the velocity of their neighbors as the sensory input to make motion decisions. This further poses great challenges in real-world applications of swarm robotics. In this letter, inspired by the chasing behavior in large-scale migrating locusts, we propose a visual attention-based swarm model to achieve collective behaviors with positional interaction. Through numerical simulations, we find the emergence of three typical collective behaviors: flocking, milling and swarming. To gain deep insights into the new proposed model, we investigate the impact of group size and sensory blindness on the emergence of collective behaviors. Moreover, by using the mean field analysis framework, we present the theoretical proof of the emergence of flocking and milling behavior. Furthermore, to validate the feasibility of our proposed model, we reproduce the flocking and milling behavior with up to 50 physical robots. Robotic experiments demonstrate the promising ability of the new proposed model to achieve collective behaviors with the absence of velocity alignment.

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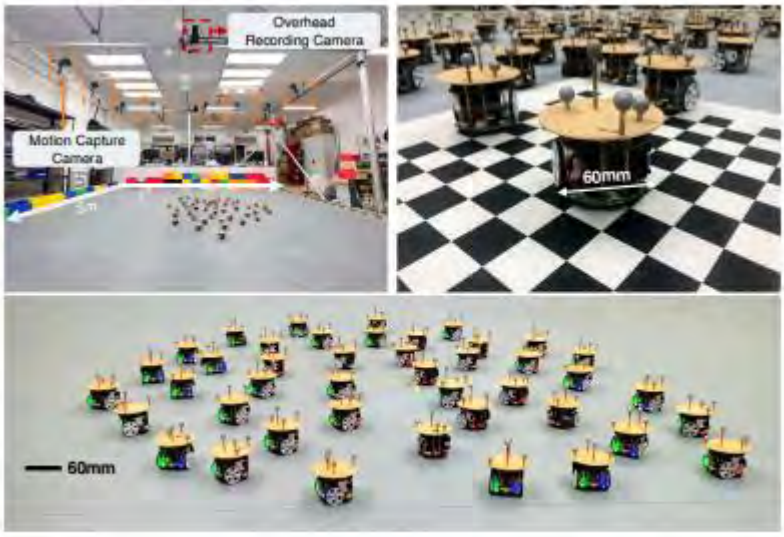

Fig. 6. The SwarmBang robotic validation system.

How NOKOV Contributes to the Research

The SwarmBang system contains up to~102table-levelrobots (60 mm×60 mm×60 mm) and a NOKOV motion cap-ture system. Due to constraints in the size of the experimental arena, we adopt up to 50 robots to validate the feasibility ofthe DLN-S model. The robot is driven by two-step motors withthe maximum speed of 25 mm/s and equipped with a 2.4 GHzRF module for communication with the server computer. The NOKOV motion capture system is used to acquire the positionsand headings of all robots. Then, the server computer performsthe computation of the DLN-S model to determine the desired velocities of each robot, which are then broadcasted to robotswith the fixed time interval Δt via a customized communication protocol.

Citation Zheng Z, Zhou Y, Xiang Y, et al. Emergence of collective behaviors for the swarm robotic through visual attention-based selective interaction[J]. IEEE Robotics and Automation Letters, 2024.

Link

https://www.researchgate.net/publication/383932719_Emergence_of_Collective_Behaviors_for_the_Swarm_Robotic_Through_Visual_Attention-Based_Selective_Interaction

Human-like acceleration and deceleration control of a robot astronaut floating in a space station

Keywords

Robot astronaut, Human modeling, Dynamic guidance model, Human-like control

Abstract

The acceleration and deceleration (AD) motions are the basic motion modes of robot astronauts moving in a space station. Controlling the locomotion of the robot astronaut is very challenging due to the strong nonlinearity of its complex multi-body dynamics in a gravity-free environment. However, after training, humans can move well in space stations by pushing the bulkhead, and the motion mechanism of humans is a good reference for robot astronauts. The contribution of this study is modeling the human AD motion in a microgravity environment and proposing a human-like control method for robot astronauts moving in space stations. Specifically, the movement and contact force data of the human body during AD motion were collected on an air-floating platform. Through human AD modeling analysis, the mechanism of human motion is discovered, and semi-sinusoidal primitives of contact forces are proposed for AD motion. Then, a dynamic guidance model of human AD motion is built to complete motion planning under contact constraints, which is used as the expected model for the AD control of robot astronauts. Benefiting from the force primitives, accurate and safe planning of human-like AD motion can be completed. The characteristics and mechanism of human AD motion have been analyzed from the perspective of optimization. Lastly, based on the proposed dynamic guidance model, the AD motion policy is mapped to the robot astronaut system via a system control method based on the equivalent mapping of dynamic responses (force, velocity and pose). Through comparative analysis with real human motion data and simulation results under different conditions, the proposed AD control method can achieve human-like motion efficiently and stably. Even when confronted with errors in the robot's contact velocities and inertia parameters, the method can significantly reduce the motion errors while ensuring stability.

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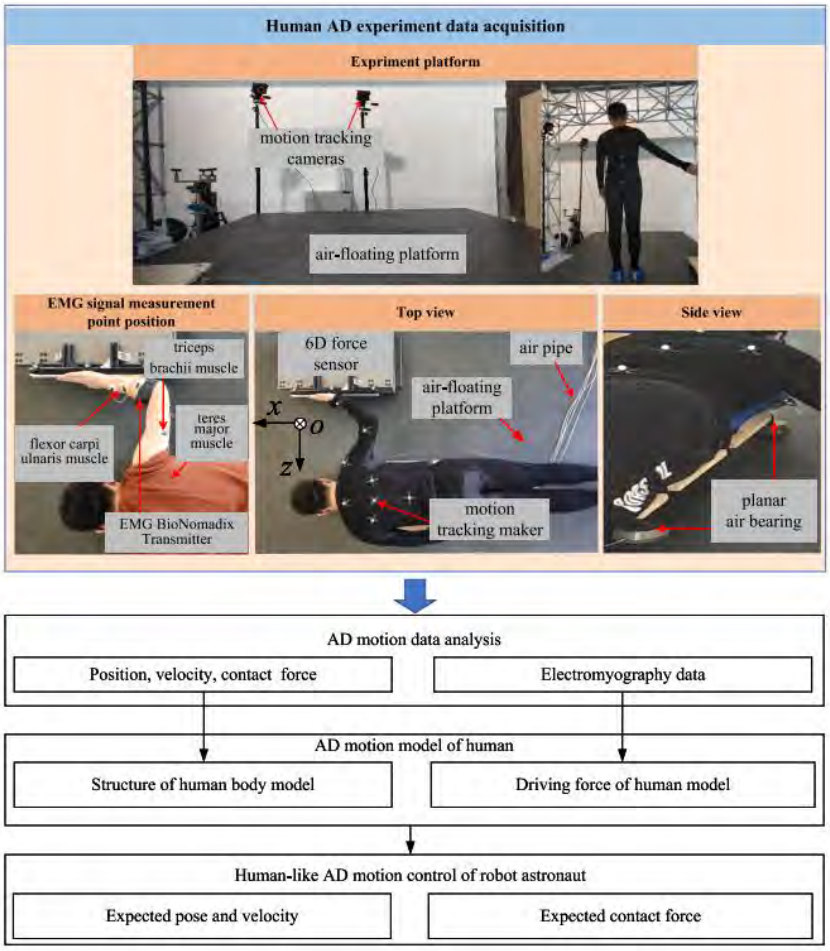

Fig. 1. Framework of human acceleration and deceleration dynamics modeling and human data acquisition experiment.

How NOKOV Contributes to the Research

As shown in Fig. l, the main components of this system include an air-floating platform, a motion tracking subsystem, a contact forcemeasurement subsystem and an EMG acquisition subsystem. A SRIM3612M six-dimensional (6D) force sensor was employed to collect theforces of human hand's contact, The human body motion data wereacquired using a NOKOV motion tracking system, and the EMG signalof the human body was collected by a BioNomadix MP160 system.

Citation Shen M, Huang X, Zhao Y, et al. Human-like acceleration and deceleration control of a robot astronaut floating in a space station[J]. ISA transactions, 2024, 148: 397-411.

Link https://www.sciencedirect.com/science/article/abs/pii/S0019057824000971

Humanoid Control Technology for Lower Limb Rehabilitation Robots Based on Human Gait Data

Keywords

gait fusion, lower-limb rehabilitation robot, humanoid control system, trajectory tracking

Abstract

The lower limb rehabilitation robot is a wearable exoskeleton bionic device that integrates robotic features with human walking characteristics. This paper explores the control strategies, gait data acquisition and processing methods, as well as the design and experimental validation of a humanoid control system for lower limb rehabilitation robots. By collecting gait data from healthy individuals using the NOKOV 3D infrared passive optical motion capture system, a gait dataset was established, and methods such as spline interpolation and Gaussian regression were employed to integrate the gait data. A humanoid control system based on real gait data was designed, utilizing a high-performance computer, R4SE controller, and joint motors to simulate gait patterns. Experimental results demonstrate that the system effectively follows target gait trajectories, achieving high trajectory tracking accuracy and smoothness, ensuring the safety and effectiveness of rehabilitation training. Future research will incorporate a more diverse group of subjects and intelligent control algorithms to enhance the system's adaptability and intelligence.

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Fig. 1. Experimental Platform.

How NOKOV Contributes to the Research

In this research, the NOKOV 3D passive infrared optical motion capture system was employed for gait data acquisition. The system comprises eight infrared optical cameras, reflective markers, calibration rods, data scaling and transmission devices, and the Seeker software for data processing, as shown in Figure 1.

Citation Gao S, Wang A, Duan H, et al. Humanoid Control Technology for Lower Limb Rehabilitation Robots Based on Human Gait Data[C]//2024 International Conference on Advanced Mechatronic Systems (ICAMechS). IEEE, 2024: 171-176.

Link https://ieeexplore.ieee.org/document/10818727

Leg Kinematic Parameter Identification of Quadruped Robots Based on a Virtual Fixed Base

Keywords

Kinematic parameter identification, Quadruped robots, Virtual fixed base, Hand-eye calibration, Least square method

Abstract

The leg kinematic parameters of quadruped robots, including connecting rod length and joint angle, often deviate significantly due to machining and assembly errors. This inaccurate knowledge can lead to foot-end position errors and ultimately affect precise state estimation and control. Directing against this issue, this paper introduces the concept of a virtual fixed base and designs a non-redundant parameter identification method. The virtual fixed base is established by 4 marking points on the body, determining a hypothetical coordinate system, which is used to solve the hand-eye calibration problem of quadruped robots. This study provides the overall process of the kinematic parameter identification method. Simulation and experiment results show that the identified kinematic parameters converge to their actual value and the foot-end position accuracy is improved by over 80% after parameter compensation.

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Fig. 7. Parameter Recognition Experimental Scenarios

How NOKOV Contributes to the Research

The NOKOV optical motion capture system was used as the measuring device, which utilized optical imaging technology to capture the coordinates of the marked points in real time with sub-millisecond accuracy.

Citation Yuan C, Ren Z, Chen H. Leg Kinematic Parameter Identification of Quadruped Robots Based on a Virtual Fixed Base[C]//2024 9th International Conference on Automation, Control and Robotics Engineering (CACRE). IEEE, 2024: 264-269.

Link https://ieeexplore.ieee.org/abstract/document/10635029

Lift enhancement of a butterfly-like flapping wing vehicle by reinforcement learning algorith

Keywords

butterfly-like; flapping wing vehicle; lift peak in upstroke; reinforcement learning; take-off

Abstract

In order to enhance the take-off lift of a butterfly-like flapping wing vehicle (FWV), we implemented an integrated experimental platform and applied a reinforcement learning algorithm. The vehicle, which has a wingspan of 81 cm and is mounted on a stand with a force sensor, is driven by two servos that are powered and controlled wirelessly. To achieve the goal of enhancing take-off lift, we used a model-free, on-policy actor-critic proximal policy optimization algorithm. After 300 learning steps, the average aerodynamic lift force increased significantly from 0.044 N to 0.861 N. This enhanced lift force was sufficient to meet the take-off requirements of the vehicle without the need for any additional aids or airflow. Additionally, we observed a strong lift peak in the upstroke after analyzing the learning results. Further experiments showed that this lift peak is directly related to the elastic release of the wing twist and the opening and closing of the gap between the forewing and hindwing in the early stage of the upstroke. These findings were not easily predicted or discovered using traditional aerodynamic methods. This work provides valuable reinforcement learning experience for the future development of FWVs.

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How NOKOV Contributes to the Research

We take a simple measurement of the opening distance between the forewing and hindwing during the flight. In figures 12(a) and (b), we place the FWV in NOKOV 3D motion capture system Mars2H to measure the motion of mark points in real time, and paste multiple infrared reflection markers on the forewing and the hindwing.

Citation Xiong M, Wei Z, Yang Y, et al. Lift enhancement of a butterfly-like flapping wing vehicle by reinforcement learning algorithm[J]. Bioinspiration & Biomimetics, 2023, 18(4): 046010.

Link https://iopscience.iop.org/article/10.1088/1748-3190/acd3cc/meta

Measurement of wing motion, deformation, and inertial forces of a biomimetic butterfly

Abstract

This paper introduces a method for measuring wing motion, deformation, and inertial forces in bio-inspired aircraft research using a camera motion capture system. The method involves placing markers on the wing surface and fitting rigid planes to determine the wing's spatial axis. This allows for describing the wing ' s rigid motion and obtaining deformation characteristics, such as deflection, twist angle, and gap distance of the forewing and hindwing. An image-based method is proposed for determining wing mass distribution, mass blocks, and mass points for inertial force measurement. The study addresses wing motion, deformation, and inertial force measurement in a real butterfly-like flapping wing vehicle and demonstrates the effectiveness of the approach. The results reveal that inertial forces play a negligible role in the generation of lift peaks and contribute minimal lift during the entire flapping cycle. Furthermore, a transitional phase between downstroke and upstroke is found in flexible wing motion, which has high lift production. This measurement approach offers a rapid and effective solution to experimental challenges in bio-inspired aircraft design and optimization.

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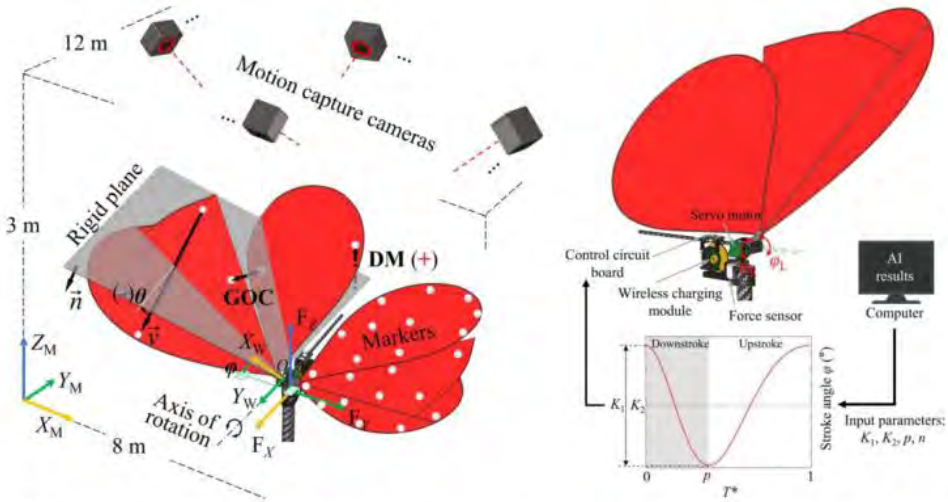

FIG. 1. Schematic diagram of the experimental setup. 16 motion capture cameras arranged around the butterfly-like FWV. φ is the angle between the rigid plane and the horizontal plane. θ is the angle between the normal vector $\vec{n}$ of the rigid plane and the chord vector $\vec{v}$ of the wing. DM is the perpendicular distance from the wing surface to the rigid plane. GOC is the distance of the gap between the forewing and hindwing (multimedia available online).

How NOKOV Contributes to the Research

The experiment employed the Mars2H optical motion capture system from NOKOV Mocap Co., Ltd.

We thank the supporting of the Project: Special Key Project of Chongqing Technology Innovation and Application Development (Grant No. cstc2019jscxzdztzx-X0044). We are also grateful to NOKOV Mocap Co., Ltd for its help with the optical 3D motion capture system.

Citation Yang A Y, Wei B Z, Zeng C S, et al. Measurement of wing motion, deformation, and inertial forces of a biomimetic butterfly[J]. Review of Scientific Instruments, 2024, 95(7).

Link https://pubs.aip.org/aip/rsi/article-abstract/95/7/075111/3304830/Measurement-of-wing-motion-deformation-and?redirectedFrom=fulltext

Perception of motion salience shapes the emergence of collective motions

Abstract

Despite the profound implications of self-organization in animal groups for collective behaviors, understanding the fundamental principles and applying them to swarm robotics remains incomplete. Here we propose a heuristic measure of perception of motion salience (MS) to quantify relative motion changes of neighbors from first-person view. Leveraging three large bird-flocking datasets, we explore how this perception of MS relates to the structure of leader-follower (LF) relations, and further perform an individual-level correlation analysis between past perception of MS and future change rate of velocity consensus. We observe prevalence of the positive correlations in real flocks, which demonstrates that individuals will accelerate the convergence of velocity with neighbors who have higher MS. This empirical finding motivates us to introduce the concept of adaptive MS-based (AMS) interaction in swarm model. Finally, we implement AMS in a swarm of ~102 miniature robots. Swarm experiments show the significant advantage of AMS in enhancing self-organization of the swarm for smooth evacuations from confined environments.

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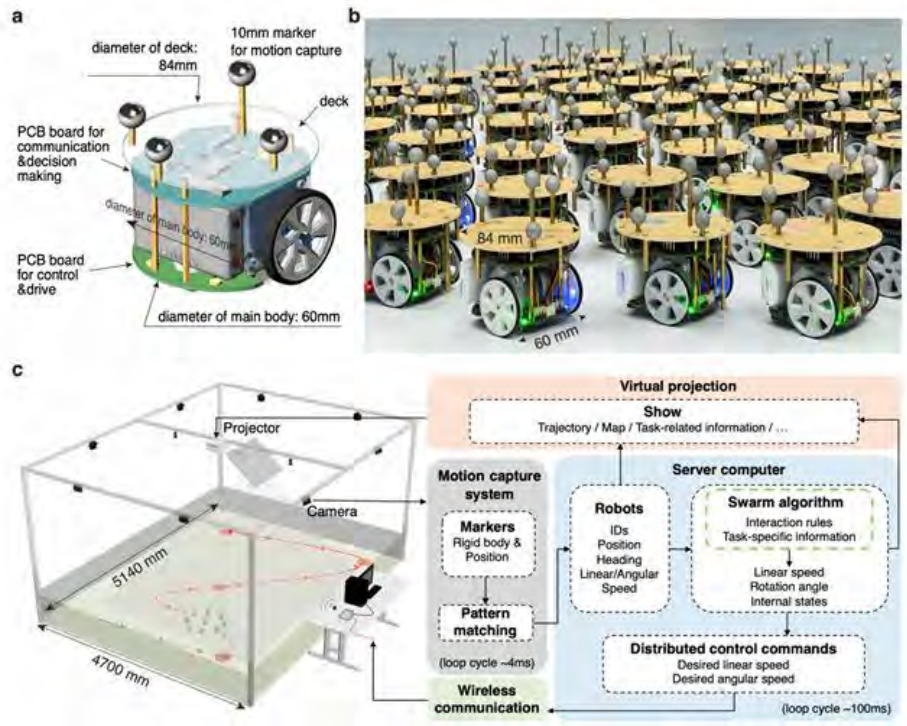

How NOKOV Contributes to the Research

A NOKOV motion capture system is used to track the robot position xðtÞ (center of body) and heading θðtÞ, from which real-time linear speed vðtÞ and angular rate ωðtÞ of the robot are obtained by differential calculation.

Citation Xiao Y, Lei X, Zheng Z, et al. Perception of motion salience shapes the emergence of collective motions[J]. Nature Communications, 2024, 15(1): 4779.

Link https://link.springer.com/article/10.1038/s41467-024-49151-x

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Real-Time Robotic Mirrored Behavior of Facial Expressions and Head Motions Based on Lightweight Networks

Keywords

Facial expressions, head motions, humanoid robot, lightweight network, mirrored behavior

Abstract

The ability of a humanoid robot to imitate facial expressions with simultaneous head motions is crucial to natural human–robot interaction. This mirrored behavior from human beings to humanoid robots has high demands of similarity and real-time performance. To fulfill these needs, this article proposes a real-time robotic mirrored behavior of facial expressions and head motions based on lightweight networks. First, a humanoid robot that can change the state of its facial organs and neck through servo displacement is developed to achieve the mirrored behavior of facial expressions and head motions. Second, to overcome the high latency caused by deep learning models running in embedded devices, a lightweight deep learning network is constructed for detecting facial feature points, which can reduce model size and improve running speed without affecting the performance of the model. Finally, a mapping relationship of 68 facial feature points to optimal servo displacements is established to realize the mirrored behavior from human beings to humanoid robots. The experimental results show that the facial feature point recognition method based on the lightweight model performs better than other state-of-the-art methods, and our head motion tracking method can maintain high accuracy compared with the gold standard optical motion capture system NOKOV. Overall, our method ensures the accurate and real-time generation of robot mirrored behavior and has a certain reference value for the efficient and natural interaction between humans and robots.

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Fig. 11. Overview of the experimental scene.

How NOKOV Contributes to the Research

Finally, the NOKOV optical motion capture system is used to capture the robot head attitude angle as the reference standard to evaluate the similarity of the head motion mirrored behavior.
To evaluate the similarity of the robotic head motion mirrored behavior, the NOKOV optical motion capture system is used as a reference system to calculate the head rotation angle in this section. Table V shows the specifications of the NOKOV. The NOKOV system can track the rotation and displacement of the carrier in 3-D space. Its rotational accuracy can reach within 0.01°, and the displacement accuracy can reach 0.20 mm. In the experiment, the robot head motion signals captured by the NOKOV system were transformed to Euler angles and used as the reference values, and the Euler angles of the human performers' head measured by our camera-based system were compared with the reference values

Citation Liu X, Chen Y, Li J, et al. Real-time robotic mirrored behavior of facial expressions and head motions based on lightweight networks[J]. IEEE Internet of Things Journal, 2022, 10(2): 1401-1413.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001011036600034

Research on Motion Transfer Method from Human Arm to Bionic Robot Arm Based on PSO-RF Algorithm

Keywords

bionic robot arm, motion transfer method, joint space mapping, PSO-RF algorithm

Abstract

Although existing motion transfer methods for bionic robot arms are based on kinematic equivalence or simplified dynamic models, they frequently fail to tackle dynamic compliance and real-time adaptability in complex human-like motions. To address this shortcoming, this study presents a motion transfer method from the human arm to a bionic robot arm based on the hybrid PSO-RF (Particle Swarm Optimization-Random Forest) algorithm to improve joint space mapping accuracy and dynamic compliance. Initially, a high-precision optical motion capture (Mocap) system was utilized to record human arm trajectories, and Kalman filtering and a Rauch–Tung–Striebel (RTS) smoother were applied to reduce noise and phase lag. Subsequently, the joint angles of the human arm were computed through geometric vector analysis. Although geometric vector analysis offers an initial estimation of joint angles, its deterministic framework is subject to error accumulation caused by the occlusion of reflective markers and kinematic singularities. To surmount this limitation, this study designed five action sequences for the establishment of the training database for the PSO-RF model to predict joint angles when performing different actions. Ultimately, an experimental platform was built to validate the motion transfer method, and the experimental verification showed that the system attained high prediction accuracy (R2 = 0.932 for the elbow joint angle) and real-time performance with a latency of 0.1097 s. This paper promotes compliant human–robot interaction by dealing with joint-level dynamic transfer challenges, presenting a framework for applications in intelligent manufacturing and rehabilitation robotics.

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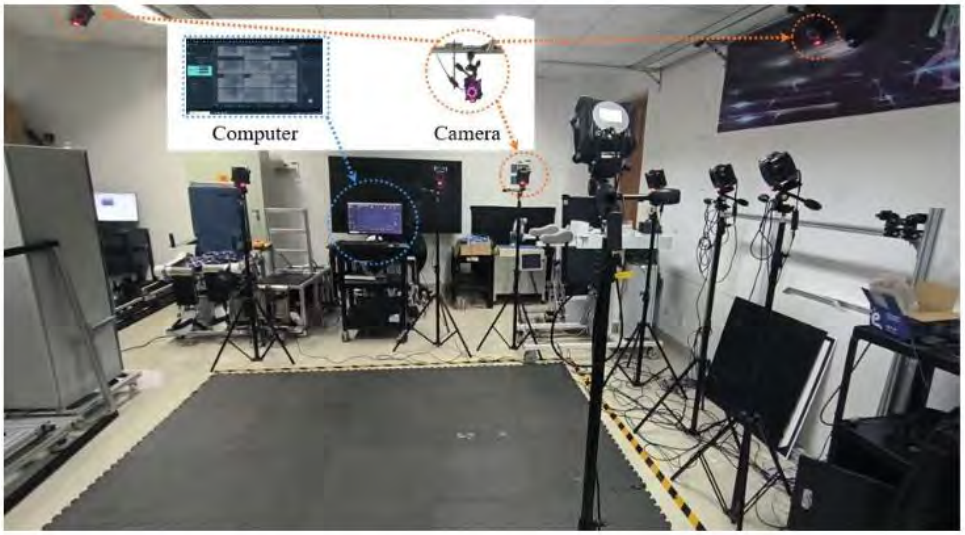

Figure 1. Global view of the Mocap system.

How NOKOV Contributes to the Research

To achieve the real-time capture of complex human arm motions, this paper employs the Nokov Mocap System, configured with twelve infrared Mars-12H cameras (100 Hz frame rate, ±0.08 mm accuracy), a host computer, and some reflective markers, as shown in Figure 1.The proprietary XINGYING 3.2 software suite provides 3D coordinate trajectory data of the reflective markers, and the end-to-end processing latency can be controlled within 3 ms.

Citation Zheng Y, Zhang H, Zheng G, et al. Research on Motion Transfer Method from Human Arm to Bionic Robot Arm Based on PSO-RF Algorithm[J]. Biomimetics, 2025, 10(6): 392.

Link https://www.mdpi.com/2313-7673/10/6/392

RoboFly.D—A Bio-Inspired Hover-Capable Flapping Wing Robot

Keywords

birds, flapping wing, hover-capable, manoeuvring flight, micro air vehicle | tail wing, ADRC controller

Abstract

Balance hovering with stability and maneuverability is acknowledged as a critical challenge for flapping wing robots, because the control system of flapping wing micro air vehicle (FWMAVs) has the characteristics of nonlinearity and strong coupling, limiting the research on FWMAVs. Inspired by the birds and insects, a novel, robust, and effective robot, named RoboFly.D, with four flapping and tail wings is proposed in this study, which realize a highly mobile and hover-capable flight. Its flapping mechanism of four wings make excellent use of the delayed-stall and clap-fling mechanisms derived from biology. The efficient flapping mechanism endows the robot with high lift, payload, and endurance. The control method of active deflection of the tail wing gives it high hovering stability. This study utilizes the fundamental principles of the Active Disturbance Rejection Controller (ADRC), which has a combination of a tracking differentiator, anonlinear combination in PD form, and an extended state observer. RoboFly.D performs better in the case of the controller with the tail wing control in rolling attitude. It has a quick and precise response in maneuvering flight, and a high sideways flight speed. RoboFly.D can conduct remote-controlled flight under outdoor conditions with a micro camera, allowing application in military reconnaissance, counter-terrorism strikes, security inspections, etc.

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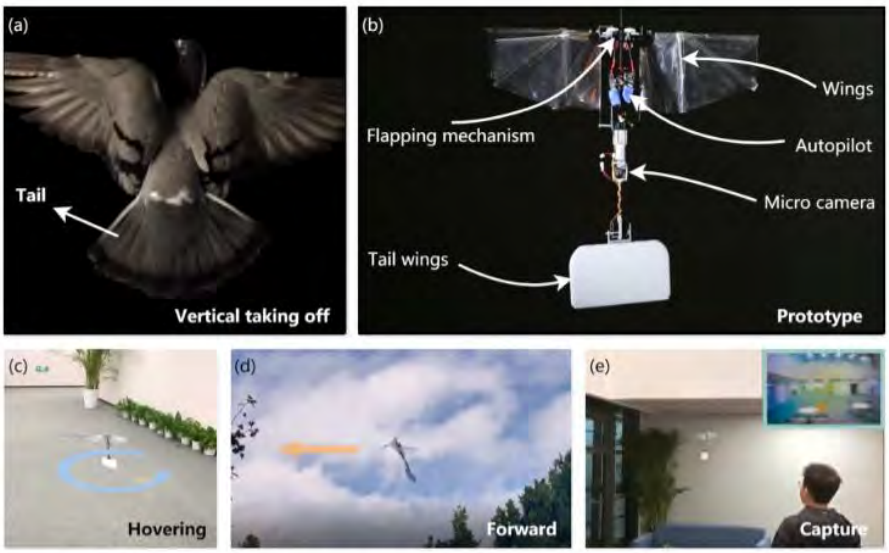

FIGURE 1 | Illustration demonstration of the RoboFly.D vehicle. (a) Vertical takeoff of birds. (b) Prototype of the reported RoboFly.D robot. (c) Hovering flight of the robot. (d) Forward flight of the robot. (e) Aerial hover shooting of the robot. [Color figure can be viewed at wileyonlinelibrary.com]

How NOKOV Contributes to the Research

The optical 3D motion capture system (Nokov, China) can obtain real - time accurate position, attitude, and six degree of freedom pose data of the robot, shown in Figure 14c. It uses 12 optical cameras to form a motion capture system, four marking points located in different planes are arranged at the top of the robot, with a diameter of 5 mm. Establish the rigid body co-ordinates of the fuselage with four marked points, record the various data of the rigid fuselage and marked points, and derive the position and attitude data during flight. The maximum forward flight speed of the robot in forward direction can ex-ceeds 4.88 m/s, and its sideways speed exceeds 3.74 m/s.

Citation Xiao S, Li C, Sun Y, et al. RoboFly. D—A Bio-Inspired Hover-Capable Flapping Wing Robot[J]. Journal of Field Robotics, 2025.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001651768300001

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Robust State Estimation for Legged Robots With Dual Beta Kalman Filter

Keywords

Legged robots, state estimation

Abstract

Existing state estimation algorithms for legged robots that rely on proprioceptive sensors often overlook foot slippage and leg deformation in the physical world, leading to large estimation errors. To address this limitation, we propose a comprehensive measurement model that accounts for both foot slippage and variable leg length by analyzing the relative motion between foot contact points and the robot's body center. We show that leg length is an observable quantity, meaning that its value can be explicitly inferred by designing an auxiliary filter. To this end, we introduce a dual estimation framework that iteratively employs a parameter filter to estimate the leg length parameters and a state filter to estimate the robot's state. To prevent error accumulation in this iterative framework, we construct a partial measurement model for the parameter filter using the leg static equation. This approach ensures that leg length estimation relies solely on joint torques and foot contact forces, avoiding the influence of state estimation errors on the parameter estimation. Unlike leg length that can be directly estimated, foot slippage cannot be measured directly with the current sensor configuration. However, since foot slippage occurs at a low frequency, it can be treated as outliers in the measurement data. To mitigate the impact of these outliers, we propose the β-Kalman filter (β-KF), which redefines the estimation loss in canonical Kalman filtering using β-divergence. This divergence can assign low weights to outliers in an adaptive manner, thereby enhancing the robustness of the estimation algorithm. These techniques together form the dual β-Kalman filter (Dual β-KF), a novel algorithm for robust state estimation in legged robots. Experimental results on the Unitree GO2 robot demonstrate that the Dual β-KF significantly outperforms state-of-the-art methods.

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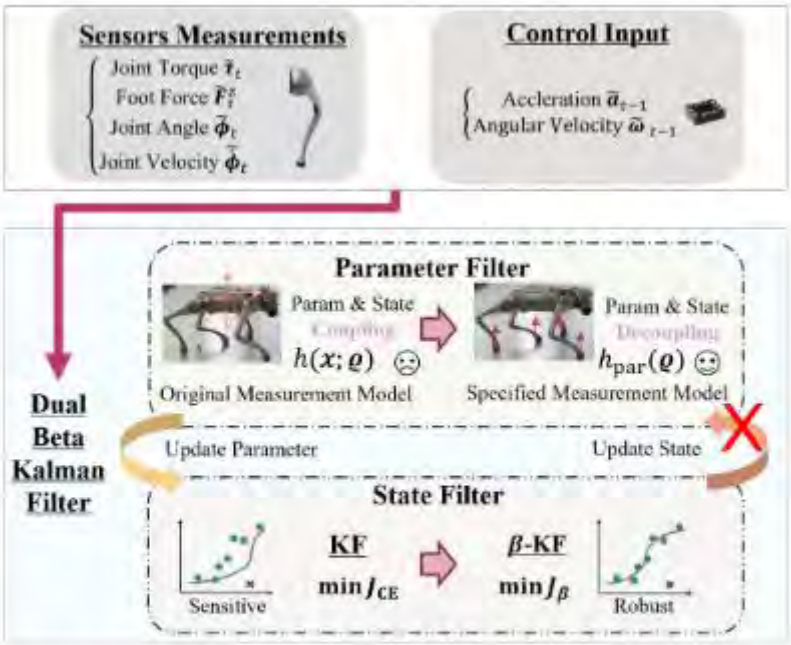

Fig. 3. Framework overview of the Dual β-KF. Proprioceptive sensor data are input to the Dual β-KF, where a state-independent parameter filter first estimates the leg length parameters. These estimates are then used by a robust state filter to determine the robot's state.

How NOKOV Contributes to the Research

In all experiments, the legged robot moves in a trot gait onflat ground, and sensor data is collected during the movement,including one IMU, 12 joint encoders, joint torque sensors,and four foot contact force sensors. Additionally, the robot'sground-truth pose is obtained from the Gazebo environment insimulation and provided by a high-precision NOKOV motioncapture system in real-world experiments.

Citation Zhang T, Cao W, Liu C, et al. Robust State Estimation for Legged Robots with Dual Beta Kalman Filter[J]. IEEE Robotics and Automation Letters, 2025.

Link https://ieeexplore.ieee.org/document/11034744

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Trajectory planning for drone landing, incorporating wind-sensing capabilities, operational and safety objectives, and reinforcement learning

Abstract

Drone flight safety and operational efficiency are challenged in the landing phase, especially in windy conditions. While flight control should be a key focus, flight trajectory also plays a critical role in landing. Inspired by the multiple objectives, wind sensory capability, and skill learning of avian species, this study proposes a reinforcement learning-based trajectory planner for a drone to perform trajectory planning in the wind, aiming to balance multiple landing-related objectives based on onboard wind sensory capability and address the safety-operational efficiency dilemma of a landing site. Through four key experiments, this study demonstrates successful training, balanced landing performance, and strong generalization capability of the trajectory planner. The experiments highlight the importance of velocity sensory capability while indicating that wind sensory capability is less critical to the trajectory planner. The proposed framework with multiple objectives, wind sensory capability, and skill learning can benefit applications such as improving drone performance.

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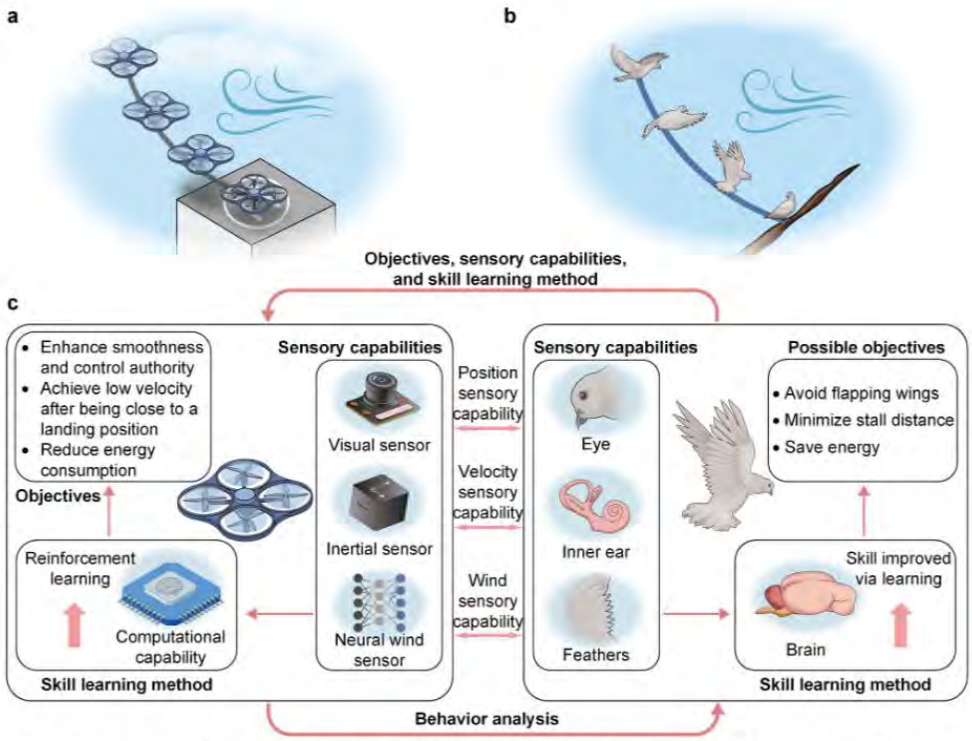

Fig. 1 | Drone landing and biological insights. a A drone performing a landing in the wind. **b** A bird performing a landing in the wind. **c** Possible objectives, sensory capabilities, and the skill learning method of a bird and those could be adopted by a drone.

How NOKOV Contributes to the Research

Experimental platform. To obtain the aerodynamic data on a drone for a neural wind sensor and investigate the performance of the proposed trajectory planner in wind conditions, a large-scale wind generator and a motion capture system are used in this study. The wind generator has a size of 4 m x 4 m and consists of1296 individually controllable fans. The wind generator can generate windat a speed of up to 12 m s. The motion capture system consists of 16infrared cameras (Nokov Mars2H) and can measure the pose of a drone at afrequency of 50 Hz.

Citation Xiong H, Li L, Zeng W, et al. Trajectory planning for drone landing, incorporating wind-sensing capabilities, operational and safety objectives, and reinforcement learning[J]. Communications Engineering, 2025, 4(1): 199.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001622329400001

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Energy Analysis of a Quadruped Robot with a Leaf Spring-Based Body

Keywords

Walking Robot, Elastic Passive Trunk Joint, Quadruped Robot

Abstract

Previous studies have revealed that incorporating a flexible body joint in the torso can enhance locomotion performance. However, the optimal design of the body joint to maximize locomotion performance has not yet been determined. To improve locomotion performance, it is crucial to minimize energy loss and utilize energy efficiently. In this study, we employ a leaf spring as the body joint in a quadruped robot and analyze the energy flow. Through this analysis, we aim to elucidate the energy dynamics within the torso and quantify the energy contributing to the robot's forward motion.

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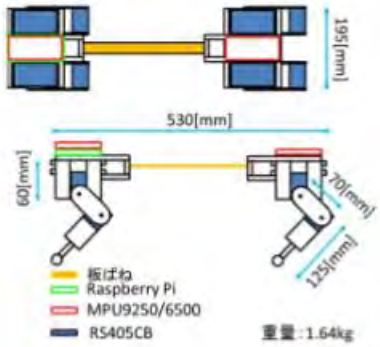
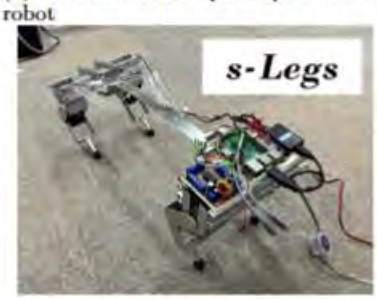


(a) Overview of the quadruped walking robot



(b) Schematic diagram showing the functions and joint positions of the quadruped robot

Fig.1: Overview and schematic diagram of the quadruped walking robot

How NOKOV Contributes to the Research

4 歩行実験
歩容はウオ-クとし，歩行周期を 2400，2600，2800，30003200，3400，3600 ms に設定した，また，デュ-ティー比は 0.7 に設定した.
モ-ションキャプチャのソフトウエアには XINGYING を使用し，カメラには NOKOV 製 Mars1.3H を採用した.カメラはロボットの左右に 2 台配置(赤丸)し，歩行デ-タを記録した歩行速度の測定方法として，50 cm の距離を測定し，開始点と終了点の床に黒のテ-プを 2 本貼付.ロボットがこの区間を歩く時間を測定し，歩行速度を算出した，歩行速度は同条件で 5 回計測した時の平均値をとる. Table 1 に測定結果を示す.

Citation 池田昌弘, 根木天徳. 板バネで構成された胴体を持つ四脚歩行ロボットのエネルギ解析[C]//ロボティクス・メカトロニクス講演会講演概要集 2025. 一般社団法人 日本機械学会, 2025: 1P1-L09.

Link https://www.jstage.jst.go.jp/article/jsmermd/2025/0/2025_1P1-L09/_article/-char/en

Hybrid crawling–jumping dynamics of a vibration-driven bristle robot

Keywords

Vibration-driven robot; Bristle robot; Hybrid dynamics; Crawl-jump gaits

Abstract

Vibration-driven bristle robots are widely treated as pure crawlers because their propulsion relies on asymmetric friction. However, when the excitation is strong, the robot can intermittently lose ground contact and jump. In this regime, a crawling-only model not only fails to capture jumping events, but also underestimates the locomotion performance gains enabled by jump-induced flight phases. Therefore, this study establishes a hybrid dynamics model of a vibration-driven bristle robot, which describes consecutive crawling and flying stages with jumping and landing events. This event-triggered hybrid model is nonlinear and non-smooth, and it yields diverse gaits ranging from period-1 to multi-period and irregular motions. Numerical analysis, dynamics simulation and prototype experiments are then used to characterize the hybrid gaits and locomotion performance. Numerical results identify two jumping mechanisms, leg lifting and push-off, and show that appreciable jumping height and average speed occur in a parameter region where push-off jumps coexist with periodic motion. Dynamics simulations provide a quantitative check of the theoretical results. Experiments on the prototype further confirm hybrid crawl–jump gaits, achieving a maximum average speed of 24 cm/s and a maximum jump height of 6 mm. The results of this study provide a more complete theoretical description of vibration-driven bristle robots by incorporating jump-induced flight phases.

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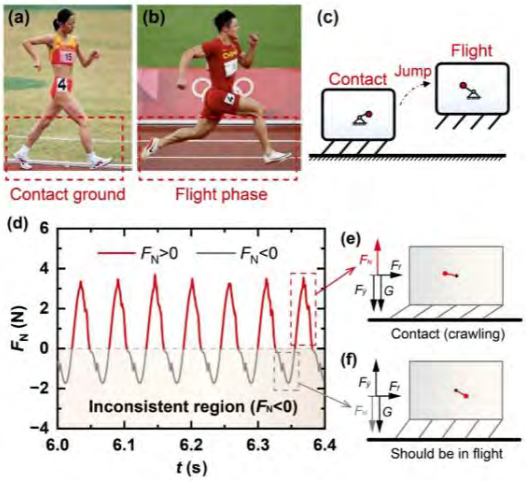

Fig. 1. Contact and flight phases in human and bristle-robot locomotion. (a) Race walking; (b) Running; (c) Contact–flight transition. (d) Normal contact force F_N; (e) Schematic of crawling motion when $F_N > 0$; (f) Schematic of the regime where $F_N < 0$.

How NOKOV Contributes to the Research

The NOKOV Motion Capture System (Mars4H) was used to obtain time histories of the robot motion in three-dimensional space. In this system, several cameras track the positions of reflection markers attached to the robot body and reconstruct their trajectories in a global coordinate frame. In addition, the SINCEVISION high-speed photography system (SH2-203-C-512) was employed to observe the locomotion process in more detail. By recording the motion of a grayscale marker on the robot with a high-frame-rate camera, this system allows us to clearly identify the different motion stages of each cycle. Fig. 12a and c show photographs of the two experimental setups, while Fig. 12b and d give their corresponding schematic diagrams.

Citation Gao Y, Li Y, Qi F, et al. Hybrid crawling–jumping dynamics of a vibration-driven bristle robot[J]. Chaos, Solitons & Fractals, 2026, 208: 118228.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001722004900001

Design and Validation of a Bionic Variable Stiffness Semi-Active Ankle–Foot Prosthesis

Keywords

Cable-suspended aerial transportation; Variational integrator; Complementary constraints; Hybrid dynamics

Abstract

Energy Storage and Return (ESR) prosthetic feet are commonly used by individuals with tibial amputations, but their fixed stiffness cannot accommodate varying walking tasks and user preferences. In contrast, semi-active prostheses can adjust stiffness through control mechanisms, though their design still leaves room for improvement in biomimetic characteristics, mass, and dynamic response. In this paper, we present a bionic, variable-stiffness, semi-active ankle–foot prosthesis. Stiffness is adjusted before each ground contact by controlling the motor to alter the length of the moment arm from the ankle joint center to the point of force application, with a range of 1.78–7.01 N·m/°. Additionally, the device features a biomimetic footplate design based on the transverse arch of the human foot, which reduces weight (total weight: 933 g) while guaranteeing support capacity. The prosthesis can precisely identify the phase for stiffness adjustment and achieve the widest range of adjustment during this phase. A unilateral tibial amputee participated in a preliminary clinical test involving variable-speed walking, stairs, and ramps. Preliminary single-subject data suggest that, compared to the subject's previous fixed-stiffness prosthesis, the newly designed prosthesis increases the range of motion, peak power, and energy storage during level walking, while reducing the adduction moment on the sound limb's knee joint. These findings offer initial support for the prosthesis' potential to improve the biomechanics of walking and other activities, providing insights for the development of biomimetic design.

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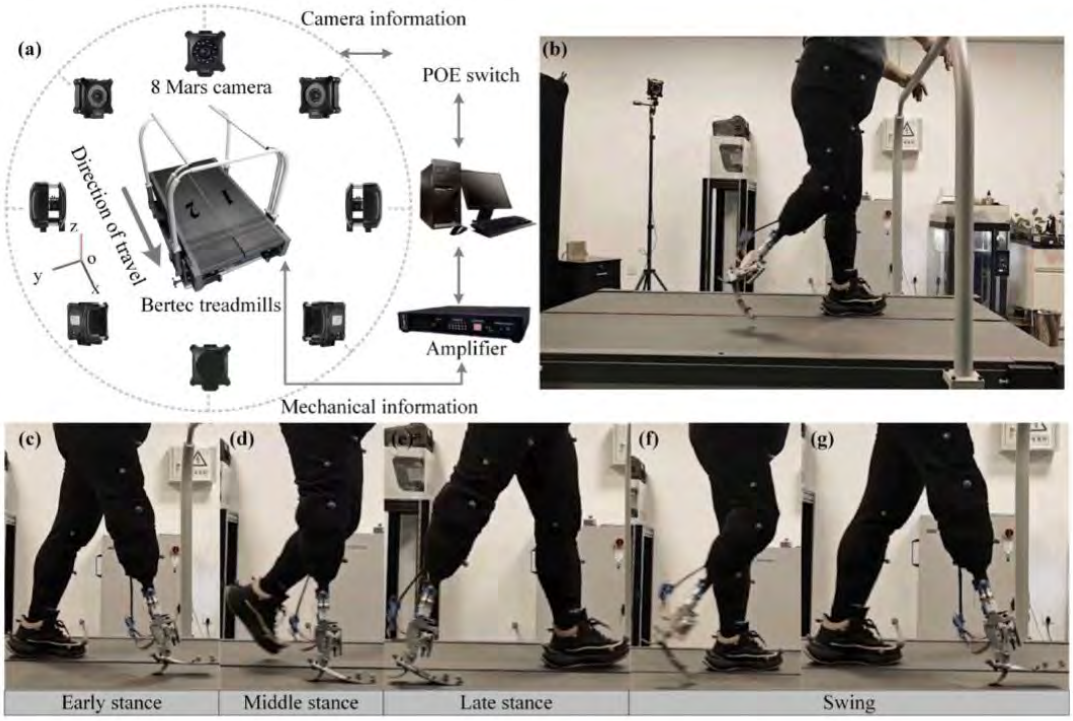

Fig. 9 Clinical testing equipment and level-ground walking test. (**a**) Clinical testing equipment: an 8-camera motion capture system and a treadmill with embedded force plates. (**b**) Anatomical marker placement on the subject, following the method described by Robertson et al. [53]. (**c**)–(**g**) Illustrate different stages of a complete gait cycle of the subjects: (**c**) Early stance (**d**) Mid stance (**e**) Late stance (**f**) Swing flexion (**g**) Swing extension

How NOKOV Contributes to the Research

The experiment was demonstrated with a 38-year-old male participant with a right-side below-knee amputation (height: 168 cm; weight: 80 kg). Ethical approval for the study was obtained from the Ethics Committee of the Second Hospital of Jilin University (log#2021072). The subject first walked on a treadmill for several minutes while wearing his proprietary prosthesis (ESR) to familiarize himself with the treadmill and the laboratory space. The proprietary prosthesis was then removed, and a certified prosthetist aligned the variable stiffness ankle–foot prosthesis with the conventional joint slot. As shown in Fig. 9a, an 8-camera motion capture system (Mars26H, NOKOV Seeker, China) was used to record gait data, and a force-measuring treadmill was employed to collect ground reaction force data. As shown in Fig. 9b, the subject was marked using the method described by Robertson et al.

Citation Ma Y, Chen W, Ren L, et al. Design and Validation of a Bionic Variable Stiffness Semi-Active Ankle–Foot Prosthesis[J]. Journal of Bionic Engineering, 2026: 1-20.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001766697400001

Morphology-aware decoupled hierarchical planning for multi-legged space robots navigation on discontinuous spacecraft surfaces

Keywords

Morphology-aware, Hierarchical planning, Space robots, Discontinuous spacecraft surfaces

Abstract

Aiming at the discontinuous terrain composed of protruding obstacles such as bolts and brackets on spacecraft surfaces, this paper proposes a Morphology-Aware Decoupled Hierarchical Planning (MADHP) method to achieve efficient and autonomous navigation for multi-legged space robots in such constrained environments. The method decouples the complex high-degree-of-freedom motion planning into three synergistic layers: semantic map construction, planar path search, and elevation trajectory optimization. First, by integrating robot specific kinematic constraints with environmental geometric features, a semantic map supporting "negotiation" is generated. Then, a synergistic Theta*-aware planner is designed to produce a global path in the 2D plane that balances path length, smoothness, and semantic compliance. Finally, a fast elevation planner based on the augmented Lagrangian and differential dynamic programming is proposed to extend the 2D path to an executable 3D trajectory that satisfies the dynamics and safety clearance constraints. Physical experiments conducted on simulated spacecraft surfaces demonstrate that MADHP can intelligently guide the robot to adopt either negotiation or circumvention strategies, significantly shortening the path length and improving planning efficiency while ensuring motion safety. This study provides a structurally clear, physically interpretable, and engineering feasible hierarchical planning framework for autonomous operations of space robots on complex discontinuous surfaces.

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Fig. 11. Spacecraft Surface Traversal Experimental System.

How NOKOV Contributes to the Research

A high precision motion capture system NOKOV [42] is employed to measure the robot's motion trajectory in real time, acquiring accurate pose data in the global coordinate frame and providing a reliable basis for subsequent trajectory tracking and performance analysis.

Citation Shilin Z, Binbin Z, Mousen C, et al. Morphology-Aware Decoupled Hierarchical Planning for Multi-Legged Space Robots Navigation on Discontinuous Spacecraft Surfaces[J]. Aerospace Science and Technology, 2026: 112933.

Link https://www.sciencedirect.com/science/article/abs/pii/S1270963826013118

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Learning Vision-Driven Reactive Soccer Skills for Humanoid Robots

Abstract

Humanoid soccer poses a representative challenge for embodied intelligence, requiring robots to coordinate agile locomotion with unreliable visual perception in dynamic environments. However, existing systems typically rely on modular pipelines that separate perception from control or assume ideal sensing, making it difficult to achieve coherent and reactive behavior under real-world perceptual limitations. In this work, we present a unified reinforcement learning–based controller that enables humanoid robots to learn vision-driven reactive soccer skills by directly coupling visual perception with locomotion control. The robot is trained in simulation to acquire soccer behaviors, and adversarial motion priors guide policy learning toward natural motion patterns. To support robust performance under imperfect sensing, we introduce an encoder-decoder architecture together with a virtual perception system that models key characteristics of onboard vision, exposing the policy to perceptual noise and detection failures during training. This design encourages the policy to internalize perceptual uncertainty and continuously adapt its motion in a closed loop. The resulting controller produces coordinated soccer behaviors using only onboard vision, including ball searching, chasing, and multidirectional kicking. It reduces ball position estimation error by 46% and shortens time-to-kick by up to 64% compared with a rule-based baseline, achieving around 90% kicking success in frontfield positions. Experiments across diverse environments and dynamic scenarios, including real RoboCup competitions, further demonstrate the robust performance of the controller. These results highlight the practical effectiveness of integrating perceptual uncertainty directly into policy learning for achieving reliable vision-driven behaviors in humanoid robots operating under real-world conditions.

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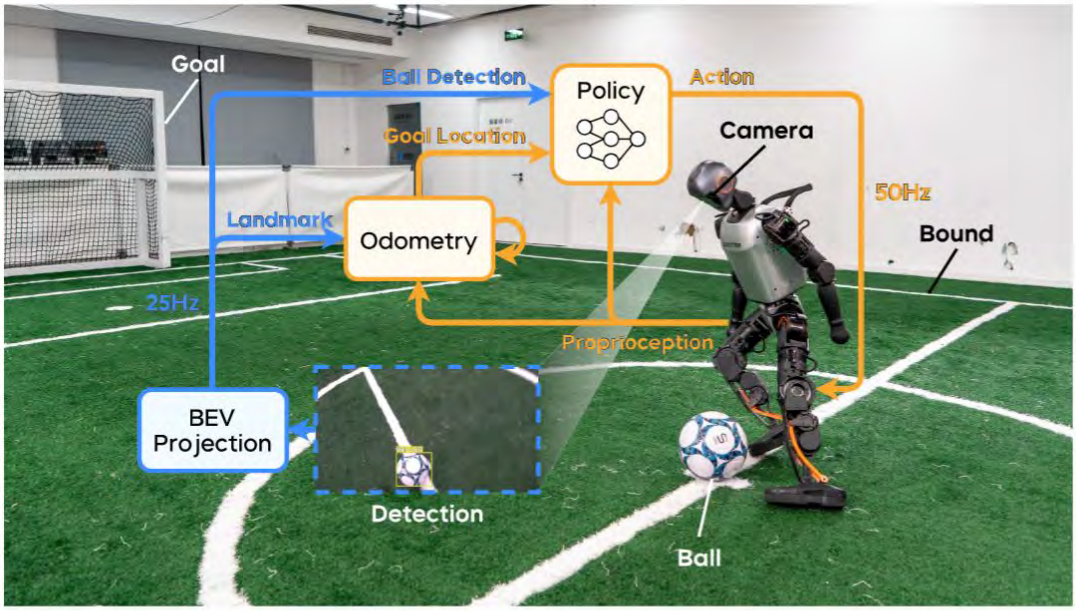

Fig. 1. System overview. The real-world robot is equipped with an onboard camera for visual perception. Image detections are projected into the BEV space. Ball detections are provided directly to the policy, and field landmarks are processed by an odometry module to infer the goal location from long-term information. The perception pipeline is designed to efficiently extract and represent visual features for the RL policy.

How NOKOV Contributes to the Research

Ground-truth positions of both the robot and the ball were obtained via a motion capture system, alongside logs of visually detected ball positions and the robot's joint positions. Positional noise was modeled using a Gaussian distribution, with variance regressed as a linear function of the relative position between the robot and the ball.

Citation Wang Y, Luo C, Chen P, et al. Learning vision-driven reactive soccer skills for humanoid robots[J]. Science Robotics, 2026, 11(117): eaed1152.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001852898700002

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Toward Reliable Sim-to-Real Predictability for MoE-based Robust Quadrupedal Locomotion

Abstract

Reinforcement learning has shown strong promise for quadrupedal agile locomotion, even with proprioception-only sensing. In practice, however, sim-to-real gap and reward overfitting in complex terrains can produce policies that fail to transfer, while physical validation remains risky and inefficient. To address these challenges, we introduce a unified framework encompassing a Mixture-of-Experts (MoE) locomotion policy for robust multi terrain representation with RoboGauge, a predictive assessment suite that quantifies sim-to-real transferability. The MoE policy employs a gated set of specialist experts to decompose latent terrain and command modeling, achieving superior deployment robustness and generalization via proprioception alone. RoboGauge further provides multi-dimensional proprioception-based metrics via sim-to-sim tests over terrains, difficulty levels, and domain randomizations, enabling reliable MoE policy selection without extensive physical trials. Experiments on a Unitree Go2 demonstrate robust locomotion on unseen challenging terrains, including snow, sand, stairs, slopes, and 30 cm obstacles. In dedicated high-speed tests, the robot reaches 4 m/s and exhibits an emergent narrow-width gait associated with improved stability at high velocity.

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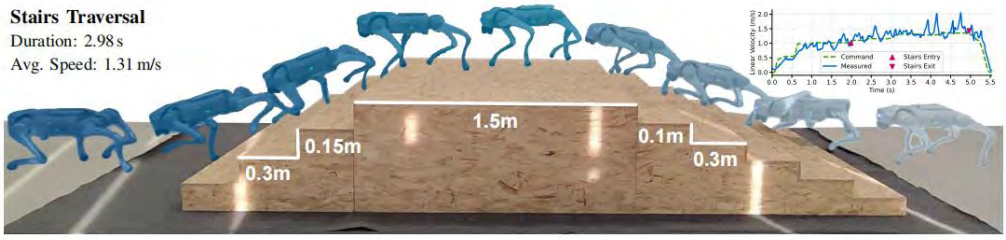

Fig. 7: Experiment on wooden stairs with a 10 cm rise and 15 cm drop. The upper-right plot depicts the velocity tracking curve captured through a motion capture system where the tracking error is 0.15 m/s.

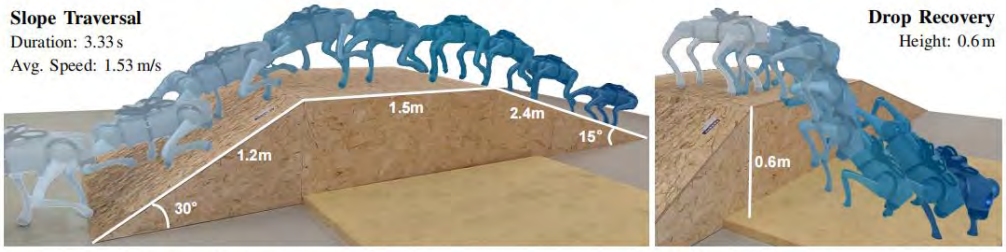

Fig. 8: Robust locomotion during slope traversal and drop recovery. The left panel highlights a 1.7 s efficiency gain on $\mu = 0.71$ slopes compared to the built-in RL baseline and the right frame verifies reliable recovery from 60 cm drops.

How NOKOV Contributes to the Research

We deployed the proposed model and baselines on a Uni tree Go2 quadruped robot. We utilize a 12-camera NOKOV Mars18H motion capture system operating at 90Hz to acquire real-time linear and angular velocity data across flat terrain and 10cm stairs by mounting five markers on the robot base. At the same time, we gather proprioceptive feedback and motor torques to derive the six specific metrics in Table II. To quantify the fidelity of these assessment methods, we compare the metric errors from both the training environ ment and our proposed framework against real-world ground truth. We specifically evaluate a model that exhibited high performance during training but suffered from significant sim to-real degradation.five markers on the robot base. At the same time, we gather proprioceptive feedback and motor torques to derive the six specific metrics in Table II. To quantify the fidelity of these assessment methods, we compare the metric errors from both the training environ ment and our proposed framework against real-world ground truth. We specifically evaluate a model that exhibited high performance during training but suffered from significant sim to-real degradation.

Citation Wu T, Guo H, Wang Y, et al. Toward reliable sim-to-real predictability for moe-based robust quadrupedal locomotion[J]. arXiv preprint arXiv:2602.00678, 2026.

Link : https://robogauge.github.io/complete/

车载双足机器人直立平衡的踝关节仿生控制

关键词

双足机器人；肌肉激活模型；仿生控制；模糊插值推理；阻抗模型

摘要

双足机器人作为典型的智能机器人，已广泛应用于军事训练、工业制造、医疗服务、交通运输等领域。车载作为主要的交通运输模式，也是双足机器人常见的活动场景。车载平台的加速或减速运动对车载双足机器人造成直立平衡干扰。目前双足机器人直立平衡控制研究较少，大多从基于模型和基于行为的角度出发，控制方法过于依赖双足机器人和其所处环境的模型构建，其自适应性和鲁棒性较差。将人体神经肌肉控制机制应用于车载双足机器人的直立平衡控制，提高实际直立平衡控制性能的仿生控制研究，具有重要的理论意义和较大的工程应用价值。

本文采用"理论、仿真、试验"相结合的思路，以车载双足机器人为研究对象，对车载双足机器人运动控制中的重要问题——踝关节直立平衡控制方法进行了深入研究。主要工作和研究结果如下：

（1）针对人体神经肌肉激活模型环路复杂且涉及模型参数繁多的问题，采用分层结构控制方法，构建了人体直立平衡踝关节肌肉分层激活模型（简称"肌肉分层激活模型"），并提出了获取肌肉牵张反射激活分量、姿态补偿激活分量和肌肉激活量等方法；针对模型输入信号与肌肉激活量不同步的问题，提出了肌肉分层激活模型的时间延迟估计方法；提出了肌肉分层激活模型增益参数优化策略，进一步提高了肌肉分层激活模型对肌肉激活量的估计精度；通过试验验证了肌肉分层激活模型的精确性，精度可达到 93%。肌肉分层激活模型可通过人体运动信号直接获取踝关节肌肉激活量，为车载双足机器人仿生控制奠定基础。

（2）针对常用的双足机器人控制方法存在灵活性和鲁棒性较差等问题，在给出双足机器人踝关节直立平衡控制性能评价指标"抗扰周期和摆动范围"的基础上，以肌肉分层激活模型为基础，研究并提出了基于踝关节肌肉驱动机制的直立平衡仿生控制方法（简称"直立平衡仿生控制方法"）。该仿生控制方法模拟人体跖屈肌肉群和背屈肌肉群的作用机制，通过构建虚拟肌肉激活模型估计虚拟肌肉激活量，通过构建虚拟肌肉力学模型得到相应的虚拟肌肉作用力，再通过构建踝关节驱动模型估计车载双足机器人直立平衡控制所需的踝关节期望作用力矩，作用于双足机器人踝关节，使得车载双足机器人在较小车载平台加速或减速运动时，能快速、准确地恢复到初始的直立平衡位置。构建了车载双足机器人直立平衡控制仿真试验平台，验证了直立平衡仿生控制方法的有效性和鲁棒性。

（3）针对车载双足机器人负载发生变化时直立平衡控制性能变差的问题，研究并提出了基于模糊插值推理的直立平衡自适应仿生控制方法。借鉴教育学中的经验学习教学法，提出了基于经验

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学习的模糊插值推理算法，当双足机器人负载发生变化时，通过模糊插值推理，更新直立平衡仿生控制方法中虚拟肌肉激活模型增益参数，保持车载双足机器人直立平衡控制效果，使得直立平衡仿生控制方法具备自适应控制能力，并进行了仿真验证。

（4）针对直立平衡仿生控制方法中肌肉力学模型结构复杂且包含许多不易观测变量的问题，将双足机器人踝关节简化为由惯性、阻尼与弹性单元组成的二阶阻抗模型，改进车载双足机器人直立平衡仿生控制方法，提出了基于时变参数阻抗模型的直立平衡仿生控制方法。通过构建踝关节时变参数阻抗模型获取踝关节抗扰力矩，构建车载双足机器人倒立摆模型计算踝关节动态作用力矩，二者一起确定直立平衡控制过程中踝关节期望作用力矩。在构建的车载双足机器人直立平衡控制仿真试验平台上，完成了仿真试验，结果表明该控制算法提高了双足机器人的直立平衡控制性能。

（5）构建了车载双足机器人直立平衡控制试验平台，在完成了踝关节力矩跟踪试验（力矩跟踪精度达到了 98.7%）的基础上，完成了 3 种直立平衡仿生控制试验和基于神经网络学习的直立平衡控制试验。试验结果表明，4 种控制方法均能满足车载双足机器人直立平衡控制要求，其中 3 种仿生控制算法直立平衡控制效果都优于基于神经网络学习的直立平衡控制方法，且基于时变参数阻抗模型的直立平衡仿生控制方法效果最好。

本文完成了车载双足机器人直立平衡的踝关节仿生控制研究，在理论研究、计算机仿真和试验平台搭建等方面都进行了有益的探索，为双足机器人在交通运输行业的推广应用奠定了研究基础。

NOKOV 度量动作捕捉在研究中的应用摘录

为了简化研究复杂度，本文假设人体左右对称，仅考虑矢状面内的人体运动。构建了肌肉分层激活模型试验平台，主要由车载平台、同步控制器、肌电信号采集系统和 Nokov 光学动作捕捉系统（上位机+8 个摄像头）等组成，其示意图如图 2-5 所示。
采用 Nokov 光学动作捕捉系统配套软件 NK-cortex 完成运动信号的后期处理工作。将试验过程中采集得到的光学信号，在 NK-cortex 软件中经模型对比、 数据滤波和平滑处理后，可得到任意 marker 点和自定义关节的位置、速度、加速度等信号。

引用格式 尹凯阳. 车载双足机器人直立平衡的踝关节仿生控制[D].武汉理工大学,2020.DOI:10.27381/d.cnki.gwlgu.2020.001994.

链接

https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C447WN1SO36whLpCgh0R0Z-i16_wNaYct1rCckkTLVqOrdM--dbUqSbmpUYfrSshhrGubu7mARlzzd4YaXxo5w5T&uniplatform=NZKPT

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仿人体下肢的单腿机器人着地缓冲特性研究

关键词

单腿机器人；着地缓冲；仿人体下肢；被动柔顺；主动柔顺

摘要

相比于轮式或履带式机器人,腿式机器人具有更优秀的移动能力和地形适应能力。腿式机器人在野外调研和地震勘探等特种作业中,具有很高的实用价值,日益成为机器人领域的研究热点。在复杂地形环境下,腿式机器人与地面接触发生碰撞,冲击力会影响其运动稳定性,甚至损坏其内部结构。人体下肢的柔顺性,使其在运动过程中表现出优异的着地缓冲特性,为此,通过仿生研究实现腿式机器人柔顺性,对于提高其移动能力非常重要。本文通过系列实验,分析人体下肢关节的运动学和动力学特性。基于分析结果,将人体下肢结构特性映射到单腿机器人上,开展着地任务下机器人着地缓冲策略的仿生研究,提高机器人的适应性和稳定性。研究工作主要包含以下方面:(1)人体着地冲击力检测与分析。设计人体着地缓冲实验方案,包括不同高度、不同着地策略下的垂直着地。采集着地过程中的地面冲击力,以及人体下肢关节运动学和动力学实验数据。探讨着地过程中人体下肢的着地缓冲机理,为仿人单腿机器人的着地缓冲策略提供参考。(2)被动柔顺策略研究。基于前述实验结果,确立基于被动柔顺的单腿机器人设计方案。基于变结构式机构和弹簧-凸轮机构,设计了一种被动柔顺关节。在零件簧片小变形条件下,建立关节力学模型并分析其变刚度特性。在物理和仿真环境中,搭建实验样机以及单腿机器人,验证该柔性关节是否让单腿机器人具有柔顺特性,研究在不同结构参数下单腿机器人的着地缓冲性能变化。(3)主动柔顺策略研究。基于前述实验结果,确立基于主动柔顺的单腿机器人设计方案。设计了一种带有电机驱动关节单腿机器人。建立了该机器人运动学和动力学模型,提出了单腿虚拟模型控制策略,并实现了对应的控制算法。在仿真环境中,搭建单腿机器人进行了垂直着地仿真验证。基于搭建的测试平台,研究在不同控制参数下单腿机器人样机的着地缓冲性能。研究发现,基于被动柔顺的单腿机器人,能够通过调节簧片的有效作用长度来调节膝关节刚度。当膝关节刚度较低或者呈现负刚度特性时,能够有效降低地面冲击力；基于主动柔顺的单腿机器人,通过改变控制参数来改变腿部等效刚度。当机器人腿部等效刚度较低时,可起到缓解地面冲击力的作用。

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人体垂直着地实验的主要实验设备包括运动捕捉系统和测力平台。通过这两套设备，采集人体在整个着地过程中下肢关节的运动学和动力学数据。运动捕捉系统选用的是 NOKOV 光学三维动作捕捉系统，采集人体在运动过程中人体运动学数据。整个动作捕捉系统主要由 8 台红外线摄像头、PC 主机、交换机和若干个反光标志点(25mm)组成。测力平台选用 AMTI 六轴测力平台（长 X 宽 X 高：400mm X 600mm X 82.5mm)，用以获取地面反作用力(Ground Reaction Force, GRF)信息。在获取人体运动学和 GRF 实验数据后，采用人体建模软件 OpenSim 进行逆动力学分析，获取人体下肢关节肌力矩信息。

引用格式 徐汉东. 仿人体下肢的单腿机器人着地缓冲特性研究[D].武汉理工大学，2021.DOI：10.27381/d.cnki.gwlgu.2021.001658.

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https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C475KOm_zrgu4lQARvep2SAkaWjBDt8_rTOnKA7PWSN5MDQvsZRiheDynOkqRxzNjEzDyj-LAFgs1yt5IEL1XrYe&uniplatform=NZKPT

腹腔微创手术机器人控制系统研究

关键词

腹腔微创手术机器人；运动学；主-从控制策略；主操作手

摘要

机器人辅助微创手术可减小患者的创伤，缩短术后康复的时间，因此受到患者的青睐。本文针对自主研发的机器人辅助微创手术系统，进行了微创手术机器人控制系统的研究，研究内容主要包括主-从直观控制、柔性手术器械运动学和主操作手操控舒适性研究。首先根据微创手术机器人的结构建立了主操作手、从端机器人和柔性手术器械运动学模型，并建立驱动绳缆长度变化与柔性器械末端位置变化的对应关系。软硬件方面：硬件系统采用上下位机的控制模式，由运动控制卡实现多轴实时运动控制，提高了系统实时性，软件系统模块化实现多机械臂主-从切换控制。控制策略方面：根据主-从异构和主-从控制特点，提出了位姿分离的控制策略实现主-从增量控制；并根基根据微创手术切口位置固定的工作特点，建立了内窥镜到手术器械坐标系的变换关系，实现了主-从直观控制。为了提高医生操控的舒适性，针对自主开发的七自由度位姿解耦的串联型主操作手提出了一种杆长优化方法。该方法根据微创手术要求，利用人机工程学和主操作手运动学建立了关于主操作手工作空间和操作灵巧度的多个优化指标，并采用组合赋权法通过合理赋予不同优化指标权重建立了主操作手杆长优化的综合性能指标。设计主操作手性能测试实验，验证了优化后的主操作手工作空间覆盖了人手极限操作空间和人手操作舒适空间，在人手极限操作空间内具有较高的灵巧度。使用自主研制主操作手在内窥镜视野下控制柔性器械，操作者通过主操作手控制器械，使器械在内窥镜反馈的图像与主操作手具有相同的运动趋势，验证了机器人系统的运动学和主-从控制策略的有效性，实验证明在所提出的运动学求解方法和主-从控制策略下，从端机器人可以在主操作手的控制下完成主-从直观操控，并通过 3D 动作捕捉系统记录主-从跟随轨迹，通过主-从跟随轨迹对比，验证了机器人系统具有良好的运动精度。最后通过小环抓取实验验证该机器人系统能在主-从式控制下实现精细化操作。

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图 5.1 主操作手

Fig.5.1 Prototype of the optimized master manipulator

图 5.2 3D 动作捕捉设备跟踪捕捉主操作手末端标记点空间坐标

Figure5.2 The 3D motion capture device tracks and captures the spatial coordinates of the end marker points of the main manipulator

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优化后的主操作手，如图 5.1 所示。为了分析主操作手工作空间对人手部操作空间的覆盖情况，要求外科医生在操作姿态下握住并移动机械手末端执行器。将反光标记点固定在末端执行器上，利用 NOKOV 公司的运动捕捉系统采集反光标记点的位置，操作者完成手持空间的运动，摄像头记录所有末端经过空间点的坐标，如图 5.2 所示，形成主手真实工作空间点云，提取边缘坐标得到主操作手手实际工作空间。将采集到位置的包络的空间被定义为工作空间，图 5.3 表示了主操作手工作空间和人手操作空间。主操作手的工作空间完全覆盖了人手的操作空间，避免了切断主-从通信来调整主操作手位置的问题。

引用格式 卜令昕.结构化果园苹果收获机器人关键技术研究[D].西北农林科技大学，2021.DOI：10.27409/d.cnki.gxbnu.2021.000038.

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机器鳄鱼运动的仿生步态规划方法

关键词

机器鳄鱼；步态规划；动作捕捉；运动稳定性；运动仿真

摘要

模仿真实动物的运动步态，是仿生机器人步态规划研究的一个重点。本文针对一种新型仿生机器鳄鱼的步态规划问题，采用动作捕捉技术获取了真实鳄鱼的运动步态。在此基础上，利用高斯牛顿法求解出机器鳄鱼的腿部关节角度，拟合得到与真实步态轨迹相似性较好的仿生步态，并分析了机器鳄鱼在该步态下的运动稳定性。虚拟样机的运动仿真实验结果表明：机器鳄鱼能用与真实鳄鱼相似的步态，以 0.3m/s 的速度向前爬行，且具备较高的稳定性。本文的研究结果为机器鳄鱼的步态规划提供了参考。

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图 2　真实步态观测实验场地

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2 鳄鱼真实步态的观测实验
2.1 观测实验
本文采用 NOKOV 三维动作捕捉系统进行鳄鱼的步态观测实验。实验共采用了 15 台 NOKOVMars 4H 动作捕捉镜头，以圆形分布在 2.4m×2.4m 区域边界上，如图 2 所示。数据处理软件以每秒 90 帧的速率记录所有标记点的空间坐标，坐标点精度为 ±0.1mm。

引用格式 黄可凡,贾文祯,韩路路等.机器鳄鱼运动的仿生步态规划方法[J].机械科学与技术,2024,43(04):566-572.DOI:10.13433/j.cnki.1003-8728.20220287.

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基于 IMU 和运动学的四足机器人对角支撑状态估计算法

关键词

状态估计；四足机器人；运动学；欠约束；惯性测量单元；对角支撑

摘要

对角支撑是四足机器人复杂动态及线性行走必备的一种状态.然而，目前尚无有效的状态估计算法，无法支撑相应控制策略.为此，提出了一种融合惯性测量单元（Inertial measurement unit, IMU）和运动学约束的状态估计算法.首先针对对角支撑状态下运动学模型欠约束带来的位姿估计难题，通过分解机身坐标系到参考坐标系的变换矩阵，简化运动学方程，并利用 IMU 提供的可信俯仰和横滚角测量值，推导获得其余四个位姿量的解析式；进一步基于腿部微分运动学和 IMU 提供的俯仰和横滚角速率，结合位姿量的导数获得线速度和偏航角速率的解析式.仿真分析验证了该算法的有效性；实验结果表明位姿估计值准确、无漂移，偏航角速率和线速度的均方根误差分别小于 2deg/s 和 9mm/s，优于现有算法且满足实际控制需求。

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图 3　运动捕捉系统和四足机器人实验场景

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现实环境中存在各种扰动因素，非点式接触的足底、IMU 的安装误差和运动学模型参数误差等实际问题，会降低状态量的估计精度，有必要验证本文算法在实际应用中的准确性和鲁棒性。为此，利用 NOKOV 光学运动捕捉系统进行了实验测试，测试场景如图 3 所示。借助该设备捕获机身和地面设定标记点的位置后，可解算出机身状态量的实时信息并作为基准数据，用于分析状态估计算法的实际性能。

引用格式 陈辉，任志刚，冯祖仁等.基于 IMU 和运动学的四足机器人对角支撑状态估计算法[J]. 控制与决策，2024,39（09）：2894-2902.DOI：10.13195/j.kzyjc.2023.0361.

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基于人体运动机理的下肢康复机器人逆动力学建模及仿人控制研究

关键词

下肢康复机器人；逆动力学模型；拟人控制器；深度学习；人体步态数据

摘要

随着社会老龄化、城市化进程的加快以及不健康生活方式的普遍存在,脑血管疾病的危险因素也普遍被显现出来。脑血管疾病常伴有肢体运动障碍,给人类生活带来极大不便。因此,恢复行走能力是患者康复的主要目标。传统的康复理疗主要依靠人工或者借助于简单的医疗设备完成,远没有达到病人的实际需求。使用康复机器人能够有效地缓解传统康复治疗中存在的缺点与不足,具有显著的优势。其中,下肢康复机器人已逐渐成为当前的研究热点。受人类下肢特征启发的仿人控制器在下肢康复机器人的研究中发挥着重要作用。然而,由于仿人控制器的非线性和强耦合特性,人体下肢康复机器人的逆动力学模型的精确性仍然是一个具有挑战性的问题。因此,本文针对基于人体运动机理的下肢康复机器人逆动力学建模及仿人控制做了研究,主要工作及研究成果包括:(1)基于人体运动机理对健康人体下肢的运动数据进行分析。首先,通过实验室的三维运动捕捉系统和三维测力平台,对人体下肢运动的步态数据、足底力数据进行测量。然后,将采集到的数据进行滤波和拟合,处理成能直接应用于下肢康复机器人仿人控制器的数据。最后,建立下肢康复机器人二连杆模型并采用拉格朗日分析的方法进行动力学分析。(2)为了进一步提高下肢康复机器人仿人控制器逆动力学模型的精确度,提出使用非参数建模的方法学习逆动力学模型。其主要思想是用健康的人体下肢主要关节的运动数据作为输入,对应的关节力矩作为输出,通过神经网络的训练来学习逆动力学模型。为保证学习到的模型能用到下肢康复机器人的仿人控制器上,本文采集的所有数据全部是健康的人体下肢运动的真实数据。此外,由于采集的数据其数据类型是基于时间序列的,因此,本文提出使用长短记忆网络(LSTM,Long Short-Term Memory)和门控循环单元(GRU,Gated Recurrent Unit)网络来学习逆动力学模型,并比较了两种神经网络的学习效果。这两种网络模型的评价指标为均方根误差(RMSE,Root Mean Squared Error)。实验结果表明,两种网络都有很好的学习效果,GRU 网络比 LSTM 网络有更强的学习能力。(3)基于人体运动机理对下肢康复机器人进行仿人控制研究。主要思想是基于健康人步态的轨迹作为仿人控制器的期望轨迹,将从逆动力学模型学习到的仿人控制器需要提供的关节力矩作为输入,并与 PD 控制器相结合进行补偿和校正,最终实现下肢康复机器人可以精确的跟踪期望的输入轨迹。该仿人控制器最终在 MATLAB simulink 平台进行了仿真和验证。

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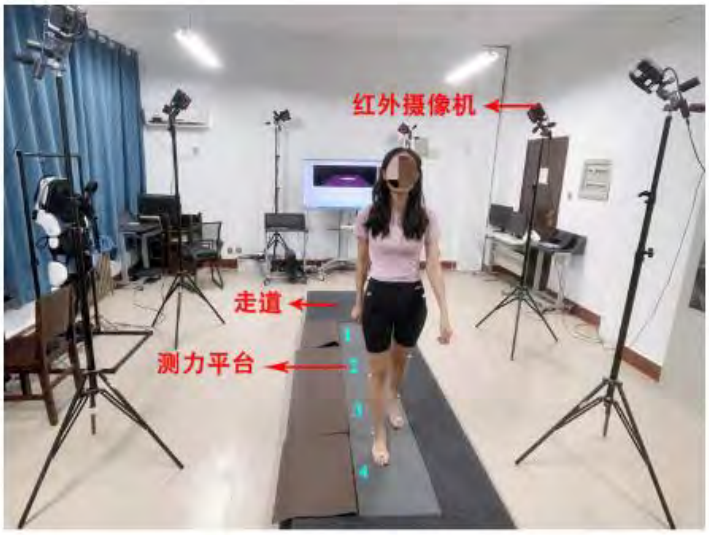

图 4-6 数据采集场景

图 4-7 Mark 点位置

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本文使用 NOKOV 三维光学动作捕捉系统进行步态数据的获取，如图 4-6 所示，该系统由 6 个红外摄像机组成，采样频率为 120Hz。红外摄像机通过捕捉贴在受试者下肢主要关节处的 8 个反光 Marker 点的运动情况来采集人体下肢运动的三维数据。Marker 点按照 Helen Hayes 标记放置协议（图 4-7）来贴定。

引用格式 宋露露. 基于人体运动机理的下肢康复机器人逆动力学建模及仿人控制研究[D].中原工学院,2023.DOI:10.27774/d.cnki.gzygx.2023.000500.

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扑翼飞行器的轨迹控制系统研究

关键词

扑翼飞行器；模型参考自适应；轨迹跟踪；系统仿真

摘要

在当今追求效率的时代里，扑翼飞行器凭借其相对于传统飞行器更高的飞行效率成为当今研究的热点。因为扑翼飞行器是利用大自然中鸟类或者飞行类昆虫的飞行方式，有着高效的飞行方式，所以其未来无论是在民用还是军事的领域都会有较大的发展前景，会是以后飞行器主要的发展趋势。

据此本文对扑翼飞行器的数学模型进行了研究，并设计了一套以基于模型参考自适应算法的轨迹控制系统，进行了控制系统系统以及实验设计，实现了扑翼飞行器的实验尝试。本文的具体研究如下：

首先，在查询阅读许多国内外文献的情况下，充分的了解国内外扑翼飞行器的发展状况后，为了进一步普及扑翼飞行器在各个领域以及行业的应用，提出了扑翼飞行器轨迹控制作为本课题的研究内容以及研究依据和意义，并阐述了扑翼飞行器的几点关键技术要求。

其次，对扑翼飞行的数学模型进行了深入的研究，基于建立的扑翼飞行器的三种坐标系统，对飞行器的力学模型以及空气动力学模型进行了建立，并且对模型进行了分析，然后推导出了飞行器的动力学方程，为本文设计控制系统打下了基础。

再次，通过研究分析现有的无人飞行器的控制系统后，设计了扑翼飞行器的控制系统，主要由模型参考自适应算法的航向控制器、传统 PID 算法的姿态控制器以及制导律组成；并使用 Matlab 软件的 Simulink 模块对设计的扑翼飞行器的控制系统进行了仿真，包括了轨迹生成模块、模型参考自适应控制器模块、飞行器本体模块和轨迹显示模块，然后对仿真的结果进行了具体的分析，检验了本文设计的控制系统的稳定性以及合理性。

最后，通过对扑翼飞行器的测绘，使用 SolidWorks 软件对扑翼飞行器的机械结构进行建模，并对不足的地方进行了改进；使用 STM32F407 为主控芯片，并用 AltiumDesigner 软件对飞行器控制器的硬件部分电路进行了搭建；将飞行器组装起来后，对小轨迹实验以及大轨迹实验平台进行搭建，为验证扑翼飞行器的可行性做好了准备。

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图 5.29 运动捕捉摄像头

Figure 5.29 motion capture camera

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5.4.1 室内实验平台探讨
在如图所示的篮球场边放置了八个高清运动捕捉摄像头。这八个高清摄像头是 Nokov(度量）科技生产的光学动作捕捉系统，摄像头特性如下:
分辨率为像素为二百二十万像素
采样频率可以高达 340 赫兹
数据延迟时间仅为 3.2 毫秒
视场角度为 56.3 °和 43.7°
镜头直径为 8 毫米
其 Nokov 反光标识点具有反光率高、尺寸型号齐全、反光效果均匀明亮的性能优势，在使用时无需连接任何线缆，不发光、不发热、无辐射、不易损坏，使用方便，效果极佳。

引用格式 夏鹏飞.扑翼飞行器的轨迹控制系统研究[D].太原科技大学，2020.DOI：10.27721/d.cnki.gyzjc.2020.000261.

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全向运动仿生腿尺寸参数优化与试验

关键词

全向运动仿生腿; 多目标优化; 尺寸参数优化; 运动学性能; 静力学性能

摘要

本文设计一款驱动固定集中、足端无伴随转动特征且具有全向运动能力的腿部机构(全向运动仿生腿 OmnilLeg),以提升全向运动仿生腿性能为目的,提出一种多目标分层优化方法对其尺寸参数进行优化。 给出了腿 部机构的运动学和静力学模型,构建了 6 项性能评价指标,包括极限步长、极限步高、两项运动学性能指标(雅可比 矩阵条件数均值、运动学性能波动情况)、两项静力学性能指标(力传递能力、力传递稳定性)。 分析了全向运动仿 生腿各尺寸参数对 6 项性能评价指标的影响程度和规律。 结合蒙特卡洛法提出了以极限步长和极限步高为主要 指标,以运动学性能和静力学性能为辅助指标,将优化目标分层的多目标尺寸参数优化方法,对全向运动仿生腿尺 寸参数进行了优化。 分析了全向运动仿生腿运动学和静力学性能,末端工作空间在 - 0 郾 07 m 臆(x、y)臆 0 郾 07 m、 5 毅臆酌臆 85 毅的区域内时,全向运动仿生腿具备更好的运动学和静力学性能。 基于优化所得的尺寸参数搭建了全向 运动仿生腿原型样机,并搭建了单腿测试平台,通过末端加载试验验证了运动学和静力学性能。 研究结果为全向 运动仿生腿进一步研究奠定基础

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(a) 原型样机

(b) NOKOV光学动作捕捉系统

图 12　单腿样机及试验设备

Fig. 12　Prototype of OmniLeg and experimental equipment

NOKOV 度量动作捕捉在研究中的应用摘录

搭建如图 12a 所示的单腿测试平台,通过监测样机在有无负载情况下运动时的足端误差变化,来验证运动学和静力学性能。如图 12b 所示,腿部足端的运动状态通过北京度量科技有限公司生产的 NOKOV 光学动作捕捉系统进行监测。NOKOV 光学动作捕捉系统由 8 台 Mars2H 动作捕捉镜头组成,并悬挂在长伊宽伊高为 4 郾 8m 伊 3 郾 6m 伊 3m 的钢制桁架之上,系统监测精度为 15mm。

引用格式　徐毓泽,卢钟岳,朱一鸣,等.全向运动仿生腿尺寸参数优化与试验[J].农业机械学报,2025,56(01):484-496.

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全向运动仿生腿运动学及动力学建模与实验

关键词

全向运动仿生腿；串并混联腿；多方法联合建模；运动学模型；动力学模型

摘要

灵巧的腿部机构使足式机器人具备了敏捷的机动性，腿部驱动固定集中、足端无伴随转 动且具有全向运动能力可以有效的提升足式机器人的运动性能。本文介绍了一种同时具备上述能力 的新型三自由度串并混联型腿部机构——全向运动仿生腿，并对该腿部机构进行数学建模。基于全 向运动仿生腿的特殊构型和运动形式，提出一种多方法联合的运动学建模方法，根据不同部分的特 点分别应用旋量法和几何法进行单独运动学建模，再结合影响系数法得到整机运动学模型。所提出 的方法可以降低从整体的角度进行建模的难度。采用拉格朗日法建立了全向运动仿生腿的动力学模 型。通过仿真及样机实验对全向运动仿生腿理论模型的正确性进行了验证。为下一步研制基于全向 运动仿生腿的足式机器人奠定基础。

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图 13 NOKOV 光学动作捕捉系统
Fig. 13 NOKOV optical motion capture system

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> *下面通过实验验证所建立数学模型的正确性。如图 12 所示，开发了全向运动仿生腿的原型样机，并搭建了单腿测试平台。本文使用 NOKOV 光学动作捕捉系统（图 13）监测腿部运动，以验证运动学模型。*

引用格式 徐毓泽,卢钟岳,朱一鸣,等.全向运动仿生腿运动学及动力学建模与实验[J].中国机械工程,2025,36(04):811-820.

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四足机器人腿部设计优化与运动特性研究

关键词

四足机器人；腿部结构；结构设计；结构优化；运动特性

摘要

足式机器人是机器人领域的重要分支,而四足机器人因其运动的快速性、稳定性好、对地形的适应性强等优点,更是足式机器人领域研究的热点。随着四足机器人技术的快速发展,在追求机器人运动速度提升的同时,对摩擦、冲击、能耗等机器人运动特性也有了更深入研究。本文基于对生物狗的仿生学研究,设计一种四足机器人腿部结构,并以其为研究对象进行结构优化,以提升机器人腿部运动性能；从落地回摆这一自然界普遍现象入手,探讨落地回摆与机器人运动特性的内在关系,从而通过足端轨迹的优化来改善机器人的运动特性表现。本文的主要工作如下:(1)通过运动捕捉实验研究了生物狗的生理结构与关节运动特性,并以此为基础设计了一种四足机器人腿部结构。初步整定腿部的各项结构参数,建立数学模型。以增大腿部工作空间、降低关节峰值力矩为目标,通过 Matlab 数值计算的方式进行腿部结构的尺寸优化；以降低静态变形、提升固有频率为目标,通过 Workbench 仿真分析的方式进行腿部结构的拓扑优化,得到优化后的四足机器人腿部结构。(2)从自然界普遍存在的落地回摆现象入手,针对设计的腿部结构,推导一般化弹簧负载倒立摆模型,并建立落地回摆的数学模型,通过理论推导结合 Adams 运动仿真的方式探讨其与摩擦、冲击、能耗这三个运动特性的定量关系,并可通过腿部足端轨迹的优化来改善上述四足机器人的运动特性。(3)加工并装配结构优化前、后两套腿部样机,搭建测试平台与控制系统。通过关节电机的电流/力矩标定实验得到电流与力矩的定量关系；通过腿部的运动实验采集关节位置、关节力矩与足端接触力数据并加以分析,对腿部结构优化的合理性与有效性进行实验验证。本文的研究成果在提升四足机器人腿部性能与运动特性方面有很好的效果与实用价值,对四足机器人的结构设计、结构优化、运动优化也提供了一定参考。

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首先以中华田园犬为对象对生物狗的生理结构以及关节运动特性进行研究，并进行了动态运动捕捉实验，提取了田园犬在运动中的关节仰角数据。并以此为参考，总结了腿部设计的基本原则并进行了腿部结构设计。明确了腿部构型、零件组成、各连杆长度以及关节转角的范围，加工腿部各个组成零件并装配成腿部样机。

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下肢康复机器人个性化步态生成及仿人控制研究

关键词

下肢康复机器人；步态生成；麻雀搜索算法；仿人控制；RBF 神经网络

摘要

随着我国人口老龄化程度逐步加剧,老年人的身体机能会随着年龄的增长而下降,容易出现诱发性疾病,尤其是脑卒中、神经系统性疾病和肢体损伤等都会导致下肢运动功能障碍患者的出现。研究表明,通过长期且有效的康复训练能够重塑运动神经,逐步恢复部分或全部运动功能。目前,我国的康复医疗资源与需要康复的人员严重不匹配,下肢康复机器人作为康复医师的"助手",它的出现在一定程度上缓解了康复医疗资源的短缺,保证康复运动的有效性和实用性。但每位患者的损伤程度具有差异性,如何为每位患者量身定制参考轨迹和和保证其有效性和安全性设计控制器成为了研究下肢康复机器人的关键之处,因此本文做了以下研究:(1)从人体的步态特征入手,构建了不同性别、不同人体的步态数据集。首先,利用三维动作捕捉系统搭建步态采集实验空间,让 21 名志愿者在实验空间内按照快、中和慢三种速度自由的各行走 20 次。最后,通过滤波、统一数据长度等一系列数据预处理,计算出志愿者在实验空间内的下肢关节角度,构建了 21(12 名男性、9 名女性)名志愿者,共 726 组步态数据的步态数据集。(2)利用步态数据集训练神经网络,来创建步态参数和身体参数与步态轨迹之间的映射关系。设计了基于广义回归网络的步态生成模型、基于 gap loss 函数的 LSTM 网络步态生成模型和基于 GLS 网络的步态生成模型。把患者的身体参数和步态参数作为步态生成模型的输入,输出为连续的关节轨迹。生成的关节轨迹与实际关节轨迹作对比,利用 MAD 分析实验结果,基于 GLS 网络的步态生成的方法,要优于前两种方法,生成的关节轨迹更接近于实际的关节轨迹,并且可以生成连续的步态轨迹。(3)保证康复训练的有效性,把步态生成模型生成的关节轨迹作为机器人的参考轨迹,设计了神经网络滑模控制和仿人神经网络滑模控制。面对无法得到精确的机器人模型,本文利用 RBF 神经网络的非线性逼近能力,逼近机器人模型中的未知项,来降低建模的难度。机器人模型易受外界干扰,利用滑模控制的抗扰动性,去抑制外界的干扰,来达到快速且有效的跟踪参考轨迹的目的。经过 Matlab 仿真验证这两种方法,设计仿人神经网络滑模控制更适合患者进行康复训练。

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（b）实际搭建的实验场景

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本文通过 NOKOV 运动捕捉系统采集了 21 名健康人的步态轨迹，测量了他们的下肢参数。将采集的步态数据经过最小二乘法滤波、截取步态周期、计算步态参数、统一数据长度等数据预处理过程后，构建了自己的步态数据集。

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III. Robotic Arm

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3D-RPP: a novel 3D vision-based Pose Perception Approach for Industrial Robots

Abstract

Enhanced by artificial intelligence, industrial robots are becoming more powerful, gaining a large variety of applications in intelligent factories. Pose perception, the aim of which is to obtain the joint coordinates of the robot in the camera coordinate system, has been proposed as a promising technology for multi-robot intelligent interaction. A large number of efforts have been made on studying robot pose perception. However, most of existing studies estimate the position of robot joints in 3D space by just using 2D color images, and perform pose perception by estimating the position of joint key points in the image, which could become infeasible in scenarios with various camera views and background environments. To address the issue, considering the information about the robot itself as a prior knowledge, we propose a novel approach for robot pose perception, named 3D-RPP. We adopt a 3D visual point cloud to estimate the rigid transformation of the camera coordinate system with respect to the robot base coordinate system, which effectively improves the accuracy of the obtained robot joint position in the camera coordinate system. We conduct extensive experiments on ROKAE xMate3 robot to investigate the performance of 3D-RPP, and the experimental results show that 3D-RPP could solve the pose perception problem well.

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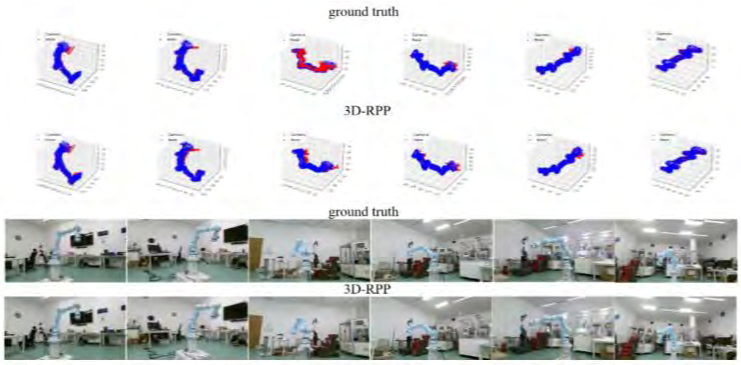

Figure 4. Visualisation of the output from the 3D-RPP model. The first two rows compare the effect of the ground truth and predicted transformation of the model in the base coordinate system (blue) to the point cloud in the camera coordinate system (red). We downsampled 1800 points from the model

How NOKOV Contributes to the Research

Prior calibration method [3][1] calibrates the global coordinate position of the interaction point. which a global coordinate system for the experimental site is established, and a fixed program to control the robot's movement route is set up. However, in practical scenarios, calibration is a complex and difficult task and it is so unintelligent and poorly adapted to the environment that it is almost only an ideal method. In high-precision localisation, high-precision location tracking devices such as Nokov. introduced as infrastructure [5]. Such devices are capable of precise robot position sensing, but are not suitable for large-scale industrial production due to their high price. Therefore, much research has been devoted to replacing these devices with low-cost methods of achieving acceptable accuracy in areas such as gait analysis [6], motion capture [7], etc.

Citation Li M, Niu J, Dou Y, et al. 3D-RPP: a novel 3D vision-based Pose Perception Approach for Industrial Robots[C]//Journal of Physics: Conference Series. IOP Publishing, 2022, 2188(1): 012013.

Link https://iopscience.iop.org/article/10.1088/1742-6596/2188/1/012013/meta

A deep learning-enabled visual-inertial fusion method for human pose estimation in occluded human-robot collaborative assembly scenarios

Keywords

Human-robot collaboration, Human pose estimation, Cross transformer, Visual-inertial fusion, Occlusion

Abstract

In the context of human-centric smart manufacturing, human-robot collaboration (HRC) systems leverage the strengths of both humans and machines to achieve more flexible and efficient manufacturing. In particular, estimating and monitoring human motion status determines when and how the robots cooperate. However, the presence of occlusion in industrial settings seriously affects the performance of human pose estimation (HPE). Using more sensors can alleviate the occlusion issue, but it may cause additional computational costs and lower workers' comfort. To address this issue, this work proposes a visual-inertial fusion-based method for HPE in HRC, aiming to achieve accurate and robust estimation while minimizing the influence on human motion. A part-specific cross-modal fusion mechanism is designed to integrate spatial information provided by a monocular camera and six Inertial Measurement Units (IMUs). A multi-scale temporal module is developed to model the motion dependence between frames at different granularities. Our approach achieves 34.9 mm Mean Per Joint Positional Error (MPJPE) on the TotalCapture dataset and 53.9 mm on the 3DPW dataset, outperforming state-of-the-art visual-inertial fusion-based methods. Tests on a synthetic-occlusion dataset further validate the occlusion robustness of our network. Quantitative and qualitative experiments on a real assembly case verified the superiority and potential of our approach in HRC. It is expected that this work can be a reference for human motion perception in occluded HRC scenarios.

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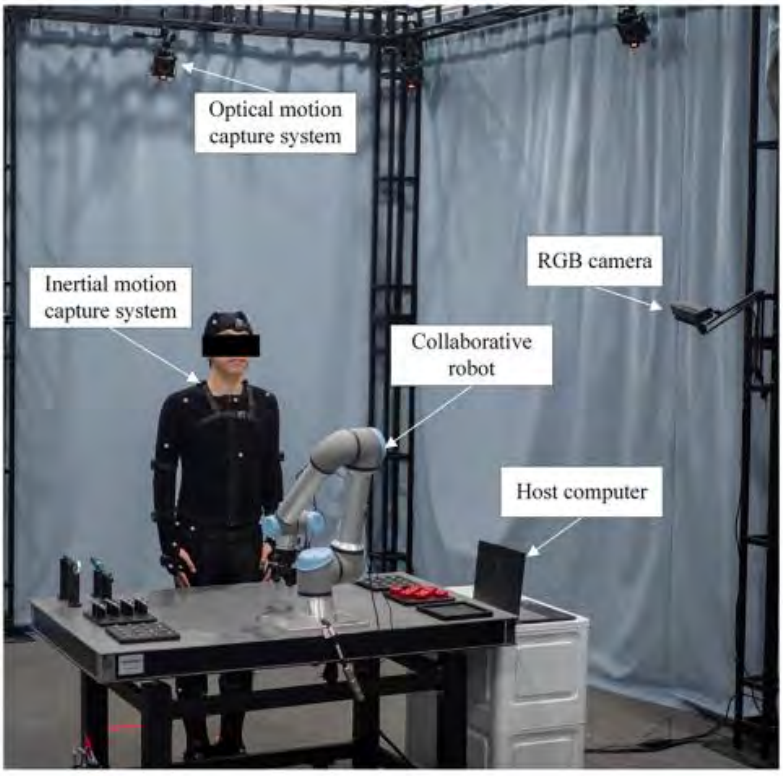

Fig. 9. Data acquisition system setup.

How NOKOV Contributes to the Research

Thus, the Nokov system with 12 Mars9H cameras is used to obtain human pose information as ground truth. The sampling frequencies of the above RGB camera, IMUs, and optical motion capture devices are respectively set to 30 Hz, 96 Hz and 120 Hz. All these raw motion data of the developed multi-modal motion capture system and the ground truth joints' positions of the optical motion capture system are collected, synchronized, and processed through ROS.

Citation Baicun Wang, Ci Song, Xingyu Li, Huiying Zhou, Huayong Yang, Lihui Wang, A deep learning-enabled visual-inertial fusion method for human pose estimation in occluded human-robot collaborative assembly scenarios, Robotics and Computer-Integrated Manufacturing, Volume 93, 2025, 102906, ISSN 0736-5845, https://doi.org/10.1016/j.rcim.2024.102906.

Link https://www.sciencedirect.com/science/article/abs/pii/S0736584524001935

A noise suppression zeroing neural network for trajectory tracking with joint angle constraints of mobile manipulator

Keywords

Mobile manipulator, Zeroing neural network (ZNN), Noise suppression, Joint angle constraints

Abstract

The trajectory tracking control (TTC) is an indispensable part in mobile manipulator (MM) application. The actual usage of the MM can be affected by factors, such as external noise interference and joint constraints. However, most of the current researches on the control of the MM only consider one of these factors. Herein, this paper presents a noise suppression zeroing neural network with joint angle constraints (NSZNN-JAC) model guided by theoretical analysis to solve the TTC problem of MM with both noise interference and joint angle constraints. The TTC problem with joint angle constraints can be transformed into time-varying nonlinear equations (TVNE) problem. The theoretical analyses verify that the NSZNN-JAC model is able to maintain convergence in the noise interference. The effectiveness and superiority of the NSZNN-JAC model are demonstrated by comparison in simulations. Moreover, the NSZNN-JAC model is applied to a physical platform which can substantiate that it is capable of performing the TTC task in the real platform.

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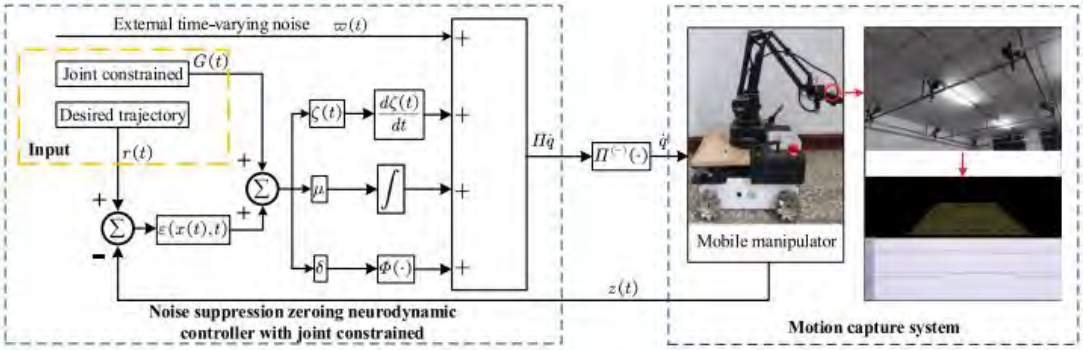

Fig. 15. Structure of experimental verification system for the MM.

How NOKOV Contributes to the Research

The optical motion capture system NOKOV is used as a measurement method to accurately obtain the actual trajectory of the MM. The maker point, depicted within the red circle in Fig. 15 , is positioned at the end-effector of the MM and is identified by NOKOV. The PC terminal is connected to the ROS of the MM through WIFI. The MM begin running the TTC task after starting the node on thePC terminal. Finally, the actual trajectory of the end-effector of the MMis captured by NOKOV and the captured data is plotted into a graph viaMatlab. The feasibility of the NSZNN-JAC model (19) can be verifiedby comparing the actual trajectory of the end-effector with the desired trajectory.

Citation Sun Z, Fei Y, Tang S, et al. A noise suppression zeroing neural network for trajectory tracking with joint angle constraints of mobile manipulator[J]. Engineering Applications of Artificial Intelligence, 2024, 133: 108173.

Link https://www.sciencedirect.com/science/article/abs/pii/S0952197624003312

A novel compliant ankle rehabilitation robotic system based on a 6-DOF robot arm

Keywords

Ankle rehabilitation robot, Alignment accuracy metric, 6-DOF robot arm, Compliance control, Motor function assessment

Abstract

Background: To address the limitations of conventional ankle rehabilitation robots in accuracy, safety, and quantitative assessment, this study proposes a novel robot arm-based system integrating compliance control.

Methods: We developed a novel robotic system using a serial 6-degree-of-freedom (6-DOF) robot arm. By defining the ankle joint center (AJC) as the midpoint between the medial and lateral malleolus, a coordinate transformation method dynamically coincides the robotic rotational center (RRC) with the AJC, validated through a novel alignment accuracy metric. A real-time gravity compensation algorithm based on a 6-axis force/torque (F/T) sensor was designed to quantify ankle joint torques. The measured torques were mapped to Modified Ashworth Scale (MAS) criteria to enable quantitative muscle tension assessment, improving objectivity over manual evaluations. Three compliance rehabilitation training modes, namely patient-passive training, patient-active training, and resistance training, are designed based on the admittance control strategy, which also support simultaneous multi-axis compliance training.

Results: The experimental results on five subjects show that the designed training modes performed well in terms of compliance and trajectory tracking. The alignment accuracy for all three training modes was less than 1.59 mm, as validated by a motion capture system. The system successfully recorded and classified torque profiles indicative of different levels of muscle tension.

Conclusion: The integration of high-precision sensing and adaptive control provides a standardized measurement platform for ankle rehabilitation, promoting the translation of robotic systems into clinical practice.

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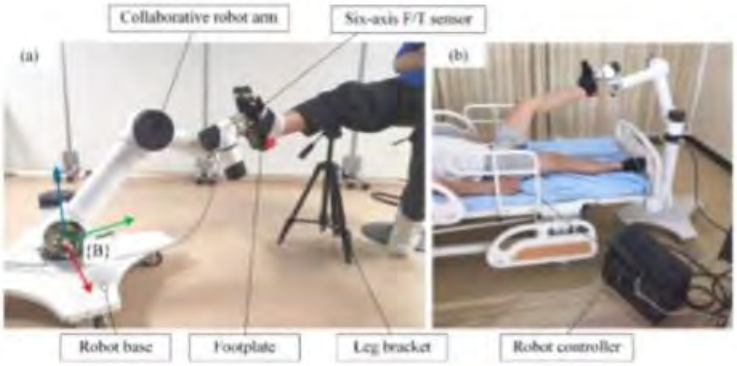

Fig. 1. Composition of the proposed ankle rehabilitation robotic system. The posture of the 6-DOF robotic arm can be adjusted to support various subject positions, including (a) seated and (b) supine configurations. The coordinate system {B} represents the fixed base frame, which serves as the reference frame for all kinematic transformations.

How NOKOV Contributes to the Research

As shown in Fig. 11, two markers were attached to the medial mal-leolus and lateral malleolus of the subject \[37]. The AJC position was obtained usingthe NOKOV motion capture system, which comprised six cameras. During patient-passive training, patient-active training, and resistance training, the three-dimensional AJC positions for each subject were captured and calculated to validate the alignment of the AJC.

Citation Jin L, Ling L, Wang C, et al. A novel compliant ankle rehabilitation robotic system based on a 6-DOF robot arm[J]. Ain Shams Engineering Journal, 2025, 16(12): 103773.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001582573400001

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A vector-based end-effector tracking and obstacle avoidance control for wheeled mobile manipulators under multi-joint position and velocity constraints

Keywords

Time-varying quadratic programming, Obstacle avoidance, End-effector tracking, Recurrent neural network, Wheeled mobile manipulator

Abstract

Obstacle avoidance is generally an additional task for a wheeled mobile manipulator (WMM) to perform end-effector tracking tasks that ensure the safety of the WMM. The WMM obstacle avoidance ensures that collisions with objects or people are avoided during operation, thus ensuring safety in the work situation and increasing efficiency in accomplishing tasks. A vector inequality-based obstacle avoidance (VIBOA) scheme is developed and analyzed, which addresses the inability of the WMM to safely avoid obstacles while completing trajectory tracking. Compared with traditional obstacle avoidance schemes, the proposed VIBOA scheme avoids the sharp stops caused by obstacle avoidance of the WMM. It enables the WMM to achieve accurate and safe obstacle avoidance, joint physical constraints and end-effector tasks. The VIBOA scheme based on time-varying quadratic programming is eventually transformed into a linear variational inequality, which is solved by linear-variational-inequality primal dual neural network (LVI-PDNN). The validity, accuracy and superiority of the LVI-PDNN-based VIBOA scheme are demonstrated through simulation comparisons with conventional schemes. Finally, experiments are conducted on a practical WMM platform to verify the physical realizability and effectiveness of the LVI-PDNN-based VIBOA scheme.

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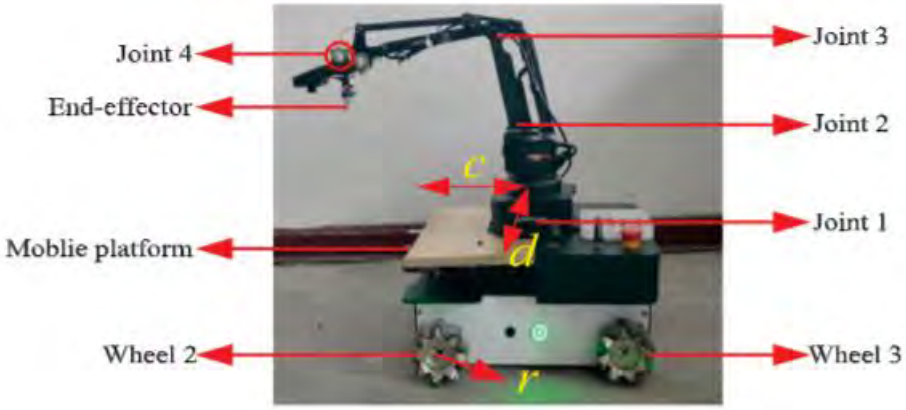

Fig. 2. Principle prototype of WMM.

How NOKOV Contributes to the Research

4.3. The WMM's verification physical platform
In this subsection, physical experiments are performed on WMM to verify the practicality of the proposed VIBOA scheme (16). The verification diagram of the platform for LV-PDNN model is illustrated in Fig. 17. The Ubuntu system is utilized to control the WMM for obstacle avoidance and trajectory tracking tasks. An optical motion capture system is employed to capture the real-time position of the end-effector of the WMM, and the captured data is plotted using Matlab software. The steps for system configuration of the NOKOV optical motion capture system are as follows: First, install the "seekerDriverl.6.2.x" and "Seeker1.6.2.1" files on Windows systems. Second, the data archive profile is created and loaded using the seeker software. Third, connect the workstation with the camera and modify the workstation's page layout so that the upper half displays a 3-dimensional view of the capture points, while the lower half shows the capture views of each camera (using a total of 9 cameras). Fourth, the end-effector position of the WMM is marked as a marker point (red circles as shown in Fig. 17, the number of marker points is 1) and placed in the center of the motion capture area (3.1 m height from the camera). The marker point of the WMM end-effector sticker is one, which is used to record the positional information of the WMM end-effector. The detailed parameter settings of the motion capture system are shown in Table 1. Sixth, the capture time is usually set to a specified time (e.g., 60 s, in which case the system automatically stops data acquisition at 60 s) or a relatively large time (e.g., 3000 s) to allow for manual start and manual stop of the capture. Seventh, the captured motion data is saved in the system and exported to other applications for subsequent analysis or animation as needed. The experimental parameters are designed as follows: $\delta = 5000$. The obstacle point O is located at [0.14, -0.1, 0.32] m.

Citation Tang S, Fei Y, Xiao X, et al. A vector-based end-effector tracking and obstacle avoidance control for wheeled mobile manipulators under multi-joint position and velocity constraints[J]. Engineering Applications of Artificial Intelligence, 2025, 160: 111864.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001547390200001

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A Visual Servo System for Robotic on-Orbit Servicing Based on 3D Perception of Non-Cooperative Satellite

Keywords

Space vehicles, Visualization, Satellites, Three-dimensional displays, Accuracy, Shape, Grasping, Servomotors, Robots, Monitoring

Abstract

The 3D perception of satellites, including both their shape and pose, is a key foundation for robotic on-orbit servicing. However, the demanding space environment-such as intense and dim illumination-presents significant challenges. Previous non-cooperative methods focus on specific geometric features like solar panel brackets or docking rings, overlooking the satellite's overall shape and increasing the risk of collisions during grasping. Additionally, satellites are often weakly textured, limiting the accuracy of 3D perception. To address these issues, we propose, for the first time, a 3D perceptionbased visual servo system of non-cooperative satellites. This system combines reconstruction and tracking to enhance shape perception and pose estimation accuracy in orbital conditions. Specifically, we employ an alternating iterative strategy to simultaneously reconstruct and track the satellite and introduce a novel constraint to fuse different cues under extreme conditions. Further, we develop a simulation environment platform, a dualarm microgravity grasping system, and an online monitoring module to enhance system capabilities for on-orbit servicing. Synthetic and real-world datasets from the simulation environment are also created for experimental validation. Results show that each module of our system achieves state-of-the-art performance.

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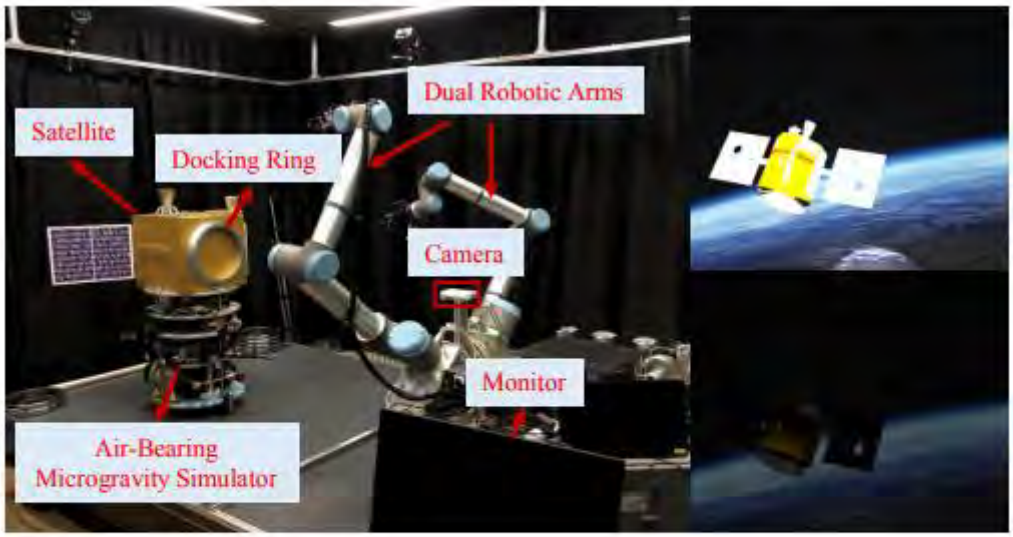

Fig. 1. The image on the left is the space environment simulation platform: the satellite is placed on a microgravity simulator for rotation, dual robotic arms for microgravity grasping, a camera placed between the arms for 3D perception, the monitor showing the results of the online monitoring. The two images on the right show extreme lighting conditions in space.

How NOKOV Contributes to the Research

The satellite's precise 3D model is obtained through laser scanning, and its ground truth poses are acquired using NOKOV motion capture equipment in conjunction with a calibration board.

Citation Zhao P, Jin L, Chen Y, et al. A Visual Servo System for Robotic on-Orbit Servicing Based on 3D Perception of Non-Cooperative Satellite[C]//2025 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2025: 1-7.

Link https://ieeexplore.ieee.org/abstract/document/11127498

Aerial Grasping via Maximizing Delta-Arm Workspace Utilization

Abstract

Workspace limitations restrict the operational capabilities and range of motion for systems with robotic arms. Maximizing workspace utilization has the potential to provide better solutions for aerial manipulation tasks, increasing the system's flexibility and operational efficiency. In this paper, we introduce a novel planning framework for aerial grasping that maximizes workspace utilization. We formulate an optimization problem to optimize the aerial manipulator's trajectory, incorporating task constraints to achieve efficient manipulation. To address the challenge of incorporating the delta arm's non-convex workspace into optimization constraints, we leverage a Multilayer Perceptron (MLP) to map the point positions to feasibility probabilities. Furthermore, we employ Reversible Residual Networks (RevNet) to approximate the complex forward kinematics of the delta arm, utilizing its efficient model gradients to further eliminate workspace constraints. We validate our methods in simulations and real-world experiments to demonstrate their effectiveness.

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Fig. 1: The aerial manipulator successfully navigates to the target point and executes high-speed grasping of the inclined object.

How NOKOV Contributes to the Research

We further validated the feasibility of our method in real-world experiments, as shown in Fig. 7. Our real-world platform consists of a quadrotor using NVIDIA Jetson Orin NX 16GB as the onboard computer and a delta arm with a hook-and-loop mechanism attached to its end-effector. The platform's state estimation is achieved by fusing data from the NOKOV Motion Capture System and the inertial measurement unit (IMU). In this experiment, the aerial manipulator needs to execute an aerial grasping task, using the hook-and-loop mechanism to pick up rectangular boxes with corresponding hook-and-loop surfaces. The box is placed on a table of a certain height, and the experiment is divided into two scenarios (Experiment 1 and Experiment 2) based on different box placement angles. Due to the limited sensing capabilities of our experimental platform, we represented the scene using pre-constructed point cloud maps. The starting and ending points of the aerial manipulator remain fixed, while the position and orientation of the boxes are obtained through the NOKOV Motion Capture System. The controller design for the aerial manipulator follows the approach outlined in [20].

Citation H. Chen, W. Deng, B. Ye, Y. Xiong, Z. Pan and X. Lyu, "Aerial Grasping via Maximizing Delta-Arm Workspace Utilization," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 12216-12223, doi: 10.1109/IROS60139.2025.11247296.

Link https://ieeexplore.ieee.org/document/11247296

An operational calibration approach of industrial robots through a motion capture system and an artificial neural network ELM

Keywords

Robot calibration · Kinematic identification · Artificial neural network · Motion capture system · DH parameter

Abstract

In the industry, robots' absolute accuracy is critical. This study provides a new calibration method to increase the robot's absolute accuracy. This method relies on a motion capture device as a measurement tool that can capture the robot's continuous motion state in any conceivable domain. Geometric parameters are determined by conducting overall measurements and assessing each joint individually, and the Extreme Learning Machine (ELM) neural network is in charge of compensating for non-geometric error sources that are difficult or impossible to model correctly or completely. The combination of model-based parameter identification and ELM neural network – based compensation approaches is an effective solution for the correction of all robot error sources. To verify the method's effectiveness and correctness, a sixrevolute joint robot GSK RB03 is used across simulation and experiment. After calibration, the robot's position accuracy ranges from 7.440 to 0.159 mm, and its orientation accuracy ranges from 3.073 to 0.077 degrees. The method's practical applicability and correctness are determined.

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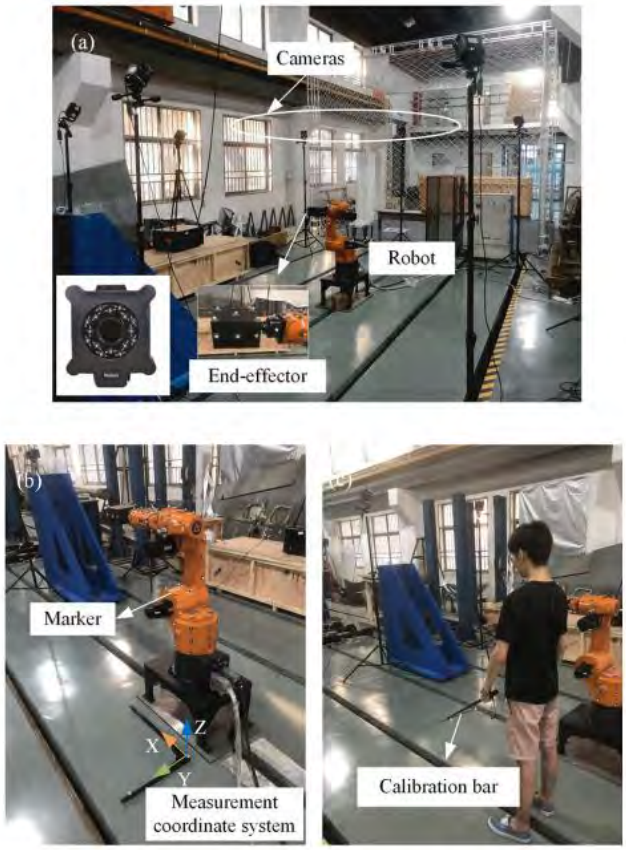

Fig. 13 (a) GSK RB03 robot and equipment, (b) the arrangement of markers and the position of the measurement coordinate system, and (c) determining the relative positions of cameras

How NOKOV Contributes to the Research

Nokov's MARS 2H is used as the motion capture system in this paper. The pixel is 2.2 MP, the highest frame rate is 380 Hz, the image resolution is 2048\1088, and the 3D measurement accuracy is ±0.15 mm. The robot is approximately arranged in the geometric center of 8 infrared high-speed cameras. An end effector is bolted to the end flange of the robot. The end-effector is designed as an aluminum hollow device, which not only ensures the strict and accurate geometric dimensions from the tool coordinate system to the end coordinate system but also considers the load requirements of the robot in Fig. 13(a).

Citation Gao T, Meng F, Zhang X, et al. An operational calibration approach of industrial robots through a motion capture system and an artificial neural network ELM[J]. The International Journal of Advanced Manufacturing Technology, 2023, 125(11): 5135-5147.

Link https://link.springer.com/article/10.1007/s00170-023-10856-w

Asynchronous Collaborative Autoscanning with Mode Switching for Multi-Robot Scene Reconstruction

Keywords

asynchronous task assignment, autonomous reconstruction, indoor scene reconstruction, multiple robots cooperation

Abstract

When conducting autonomous scanning for the online reconstruction of unknown indoor environments, robots have to be competent at exploring scene structure and reconstructing objects with high quality. Our key observation is that different tasks demand specialized scanning properties of robots: rapid moving speed and far vision for global exploration and slow moving speed and narrow vision for local object reconstruction, which are referred as two different scanning modes: explorer and reconstructor, respectively. When requiring multiple robots to collaborate for efficient exploration and fine-grained reconstruction, the questions on when to generate and how to assign those tasks should be carefully answered. Therefore, we propose a novel asynchronous collaborative autoscanning method with mode switching, which generates two kinds of scanning tasks with associated scanning modes, i.e., exploration task with explorer mode and reconstruction task with reconstructor mode, and assign them to the robots to execute in an asynchronous collaborative manner to highly boost the scanning efficiency and reconstruction quality. The task assignment is optimized by solving a modified Multi-Depot Multiple Traveling Salesman Problem (MDMTSP). Moreover, to further enhance the collaboration and increase the efficiency, we propose a task-flow model that actives the task generation and assignment process immediately when any of the robots finish all its tasks with no need to wait for all other robots to complete the tasks assigned in the previous iteration. Extensive experiments have been conducted to show the importance of each key component of our method and the superiority over previous methods in scanning efficiency and reconstruction quality.

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How NOKOV Contributes to the Research

For experiments in reality, we use Turtlebots3 instead due to its lower price. Each robot is equipped with a RealSense Depth Camera D435i, as well as an RPLIDAR A2M8 360° LiDAR scanner and Nokov motion capture cameras (https://www.nokov.com/). When the robots move beyond the capture range of the Nokov, the LiDAR scanners can track the robots' locations as well.

Citation Guo J, Li C, Xia X, et al. Asynchronous collaborative autoscanning with mode switching for multi-robot scene reconstruction[J]. ACM Transactions on Graphics (TOG), 2022, 41(6): 1-13.

Link https://dl.acm.org/doi/10.1145/3550454.3555483

Bimanual Regrasp Planning and Control for Active Reduction of Object Pose Uncertainty

Keywords

Grasping uncertainty, regrasping, bimanual manipulation

Abstract

Precisely grasping an object is a challenging task due to pose uncertainties. Conventional methods have used cameras and fixtures to reduce object uncertainty. They are effective but require intensive preparation, such as designing jigs based on the object geometry and calibrating cameras with high-precision tools fabricated using lasers. In this study, we propose a method to reduce the uncertainty of the position and orientation of a grasped object without using a fixture or a camera. Our method is based on the concept that the flat finger pads of a parallel gripper can reduce uncertainty along its opening/closing direction through flat surface contact. Three orthogonal grasps by parallel grippers with flat finger pads collectively constrain an object's position and orientation to a unique state. Guided by the concepts, we develop a regrasp planning and admittance control approach that sequentially finds and leverages three orthogonal grasps of two robotic arms to actively reduce uncertainties in the object pose. We evaluated the proposed method on different initial object uncertainties and verified that it had good repeatability. The deviation levels of the experimental trials were on the same order of magnitude as those of an optical tracking system, demonstrating strong relative inference performance.

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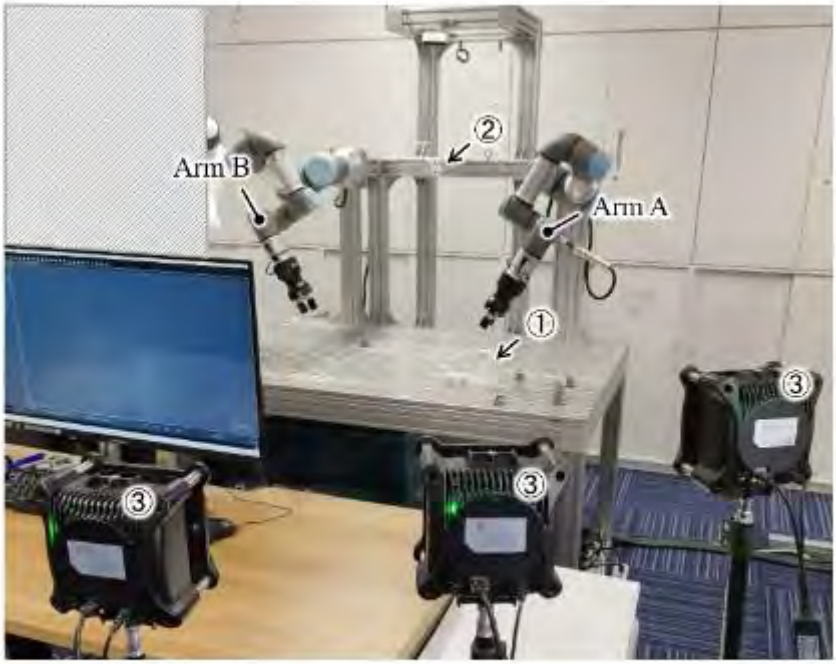

Fig. 7: Bimanual platform used in the experiments. ① Target object with optical markers. ② Markers for global reference. ③ Cameras used for detecting optical markers.

How NOKOV Contributes to the Research

Our experimental platform consists of two UR3e robots.Their setup is shown in Fig. 7. Each robot is installed witha Robotiq Hand-E gripper. The opening range of the gripper is 0~50 mm. The regrasp planning is performed using the WRS simulation environment. The coordinate system of the platform is defined at the back of the robot, with its originat the intersection of the central plane between the two robot arms and the ground. Thex-axis points toward the monitor inthe figure. They-axis points towards the first arm. Thez-axis points upward. For comparison, we attached optical markers to both the objects and the robots, and tracked the poses of the resulting rigid bodies using three tracking cameras.The poses estimated by the proposed method were compared with those captured by the optical tracking system to evaluate the method's performance. The tracking system provides a detection accuracy of±0.5 mm.

Citation Nagahama R, Wan W, Hu Z, et al. Bimanual Regrasp Planning and Control for Active Reduction of Object Pose Uncertainty[J]. IEEE Robotics and Automation Letters, 2025.

Link https://ieeexplore.ieee.org/document/11037521

BnB-Based Robust PnP Pose Estimation Method for Outliers

Keywords

Perspective-n-Point, branch and bound (BnB), dimensionality reduction, singular value decomposition (SVD), robustness

Abstract

The Perspective-n-Point (PnP). problem is a fundamental issue in the field of computer vision. However, the PnP problem is susceptible to the influence of outliers. In this letter, we introduce a robust PnP pose estimation method based on the Branch and Bound (BnB) algorithm. Considering that the computational complexity of the BnB method is related to the dimensionality of the parameter space, we construct a cost function based on the maximization of the consensus set for the parameter RRTtt. This approach reduces the search from a 6D space to a 3D space, thereby decreasing computational complexity and reducing computation time. Subsequently, we derive the upper and lower bounds for the BnB algorithm and perform pruning until convergence to obtain the global optimal solution for this parameter. After identifying corresponding point pairs that meet the inlier threshold, we employ Singular Value Decomposition (SVD) to solve for the translation and rotation parameters from this parameter. Finally, extensive comparative studies across synthetic and real datasets reveal that our method delivers accurate pose estimation and demonstrates robustness against noise and outliers, offering a viable solution for PnP issues in practical applications.

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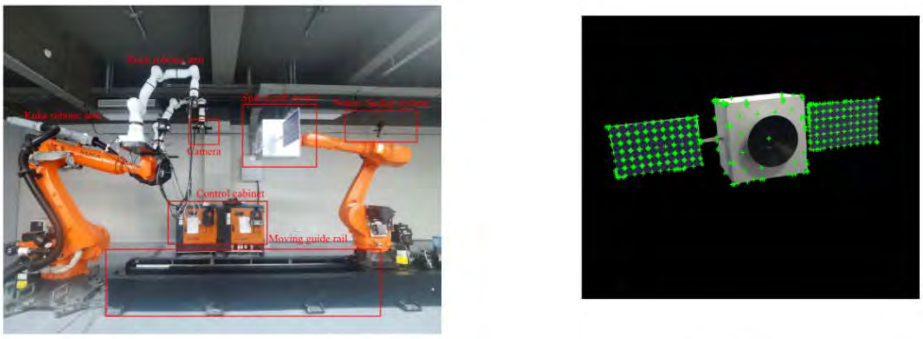

(a) (b)

Fig. 10. (a) The on-site experimental setup to capture the spacecraft pose, (b) Feature point extraction results of the spacecraft.

How NOKOV Contributes to the Research

The setup is further enhancedby the inclusion of eight infrared cameras positioned aroundthe ceiling, forming a comprehensive motion capture system(Nokov Seeker). On this platform, the robotic arm drives the spacecraft model on it to perform 20 different rotational and translational movements. Simultaneously, data acquisition was carried out using the NOKOVcalibration framework in conjunction with a monocular camera for thorough data collection.

Citation Long C, Hu Q, Jiang C, et al. BnB-Based Robust PnP Pose Estimation Method for Outliers[J]. IEEE Robotics and Automation Letters, 2025.

Link https://ieeexplore.ieee.org/document/11011668

Compensation Method for Lever-Arm Effect in Multi-IMU Measurement of Cable-Driven Hyperredundant Manipulators

Keywords

Cable-driven hyperredundant manipulators (CDHRMs), distributed multi-IMU, error-state Kalman filter, lever-arm effect compensation, screw theory

Abstract

Owing to structural design limitations, it is usually challenging to install traditional encoders or other joint measurement devices on cable-driven hyperredundant manipulators (CDHRMs). As an alternative, inertial measurement units (IMUs) can be used to measure the relative attitude of adjacent links to obtain joint information. However, the spatial offset between the IMU's installation position and the rigid body's center of rotation can cause a lever-arm effect, which may increase joint angle measurement errors and degrade the accuracy of the manipulator's end-effector trajectory estimation. This article proposes a lever-arm effect compensation method for a distributed multi-IMU system to improve the accuracy of end-effector trajectory estimation. First, we establish the forward kinematics model of a hyperredundant manipulator based on the screw theory. Subsequently, the mechanism of the lever-arm effect is reanalyzed using the screw theory. Based on this mechanism and in conjunction with the kinematic model, a compensation method for the lever-arm effect in a distributed multi-IMU measurement system is proposed. Finally, we develop a pose estimation algorithm for the manipulator end-effector based on distributed IMUs, which demonstrates high effectiveness even in the presence of the lever-arm effect. The effectiveness of the proposed compensation method has been validated both through simulations and practical experiments. In the prototype experiment of the end-effector trajectory estimation task, we design and manufacture a distributed multi-IMU measurement system. The results show that, compared with the method without compensation and the conventional compensation method, the proposed method achieves higher accuracy.

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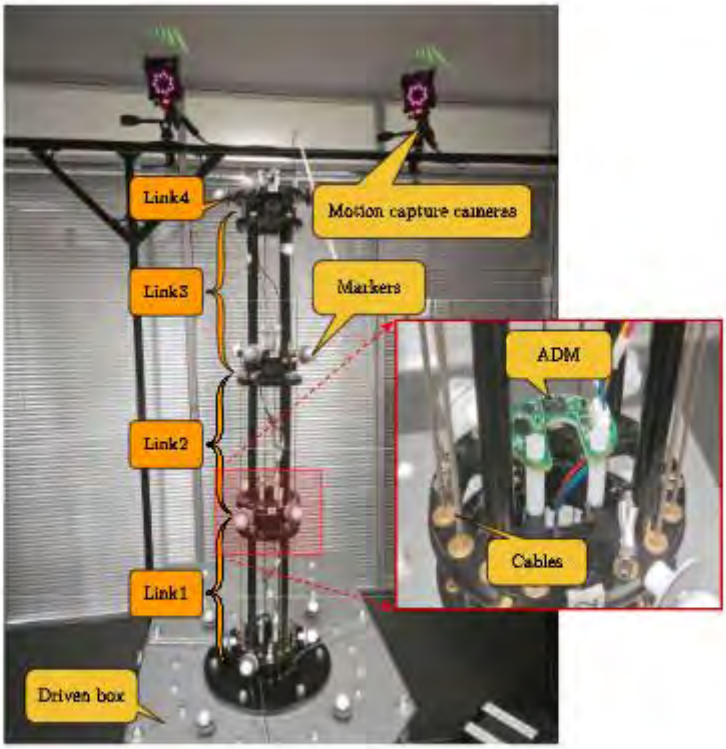

Fig. 14. Composition of the experimental manipulator.

How NOKOV Contributes to the Research

The manipulator is positioned within the range of motion capture cameras (we use the NOKOV OMCS), as depicted in Fig. 14. Cables are controlled by the driven box. Each link of the manipulator is equipped with an ADM, forming the measurement network as shown in Fig. 2. The Orin unit generates PPM signals to synchronize the timing of ADMs and collects data from each ADM for overall computation. Motion capture markers are attached to each link to form a rigid body for tracking in the OMCS software, enabling accurate pose tracking of the links. Although the desired joint angles matched those indicated in Fig. 10, the actual end-effector trajectory deviated from the simulated environment due to the inherent inaccuracies of cable-driven motion under open-loop control.

Citation Xu L, Zou W, Guo J, et al. Compensation Method for Lever-Arm Effect in Multi-IMU Measurement of Cable-Driven Hyper-Redundant Manipulators[J]. IEEE Transactions on Instrumentation and Measurement, 2025.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001500436900015

Design and Demonstration for an Air-bearing-based Space Robot Testbed

Keywords

Actuators, Trajectory planning, Software algorithms, Switches, Transforms, Aerospace electronics, Software systems

Abstract

Multi-arm space robots will play the important role in the future space activities, such as on-orbit servicing, manufacturing and active debris removal, requiring more advanced techniques for the complicated planning and control problem. In order to verify the algorithms developed for them on the earth, this paper describes the design and demonstration procedure for an air-bearing-based simulator. Firstly, the detailed design process is presented to overview both the hardware and software systems. Then the planar mathematical model of the simulator along with actuators configuration is proposed, following by the switch strategy for hybrid actuator and command transformation method. Finally, the experiment is executed to show the effectiveness and performance.

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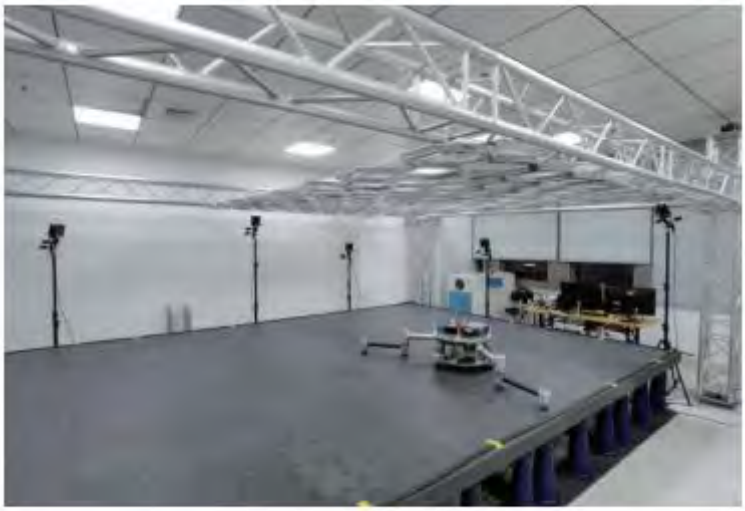

Fig. 1. System Overview

How NOKOV Contributes to the Research

The Nokov motion capture system consists of eight Mars 2H cameras, POE Hub connector, Markers installed on the simulator and software on the PC. The original optical data of the Markers is collected by the infrared cameras with 2.2M resolution, 380Hz frequency and 2.4ms latency. Then the data is synchronized and sent to PC through POE Hub connector. Finally, the required pose information is calculated and broadcast to the simulator through WiFi, leading to the total measurement latency of 6ms.

Citation Liu Z, Lin T, Wang H, et al. Design and demonstration for an air-bearing-based space robot testbed[C]//2022 IEEE International Conference on Robotics and Biomimetics (ROBIO). IEEE, 2022: 321-326.

Link https://ieeexplore.ieee.org/abstract/document/10011657

End-Effector Trajectory Tracking Control of Stacking Robot Based on LuGre Model

Keywords

Stacking robot, LuGre model, fuzzy system, terminal trajectory

Abstract

In order to realize the accurate tracking of the end-effector trajectory of the stacking robot, an end-effector trajectory tracking control method based on LuGre model is proposed. First, the dynamic model of the stacking robot including joint friction is established. In order to eliminate the influence of the joint friction of the stacking robot, the LuGre friction model is introduced into the stacking robot system. The genetic algorithm and the two-step dynamic response method are used to identify the static and dynamic parameters of the LuGre friction model. The identified parameters are feed-forward compensated to the controller, which greatly improves the robustness of the controller. Second, aiming at the problem that it is difficult to obtain the model parameter information of the stacking robot, an adaptive double fuzzy backstepping sliding mode controller is designed. The double fuzzy system is used to realize the online estimation of the model information parameters while the switching term of the sliding mode controller is continuous, and the adaptive adjustment robust gain is realized. Furthermore, the chattering problem caused by the sliding mode controller is eliminated and the stability of the system is proved. Finally, the experimental study on the trajectory tracking control of the terminal of the stacking robot is carried out. The results show that the method can well realize the joint trajectory and end-effector trajectory tracking control of the stacking robot. The mean error between the relative position points of the spatial trajectory is within 2.47 mm, and the chattering phenomenon is obviously improved.

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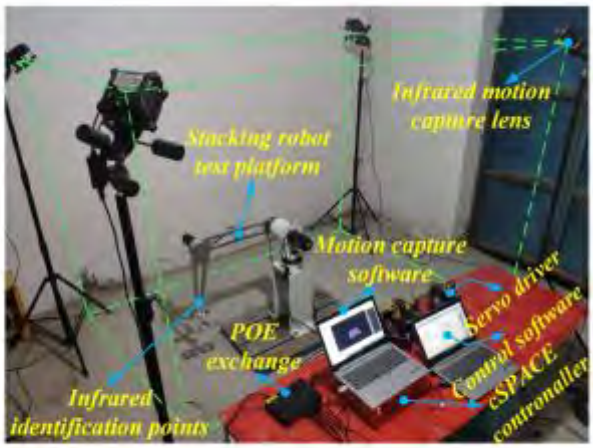

Fig. 9. End-effector trajectory tracking test system.

How NOKOV Contributes to the Research

As shown in Fig.9, the test system includes stacking robot body, servo controller, CSPACE controller, NOKOV motion capture system and corresponding software. In the end-effector trajectory tracking test system.
The NOKOV motion capture system obtains the motion trajectory ofthe stacking robot arm in real-time, and then obtains the actual motion end-effector trajectory.

Citation Gu C, Liu S, Bao W, et al. End-Effector Trajectory Tracking Control of Stacking Robot Based on LuGre Model[J]. IEEE/ASME Transactions on Mechatronics, 2025.

Link https://ieeexplore.ieee.org/document/10843950

NOKOV Motion Capture +86-10-64922321 Info@nokov.cn www.nokov.com

Fast calibration method for industrial robot kinematics based on motion capture system

Abstract

This paper proposes a fast kinematics calibration method for industrial robots (IRs). Unlike existing approaches, the proposed method focuses on rapid calibration in complex and temporary IR-related scenarios. To achieve this purpose, the IR kinematic calibration is divided into four specific application situations, each using partial modules from the comprehensive calibration algorithm to streamline the process. The complete calibration method consists of two steps: first, determining the IR's joint axes through sequential joint movements and obtaining rough kinematic parameters, and second, refining these parameters using stochastic gradient descent within an optimization framework. In addition, the existing calibration methods typically ignore the positions of the intermediate links, which impacts IR obstacle avoidance. This paper proposes obstacle-avoidance auxiliary points to address this issue. Finally, simulation and experiment, conducted using a motion capture system, demonstrate that the proposed method can achieve fast, accurate calibration in complex scenarios.

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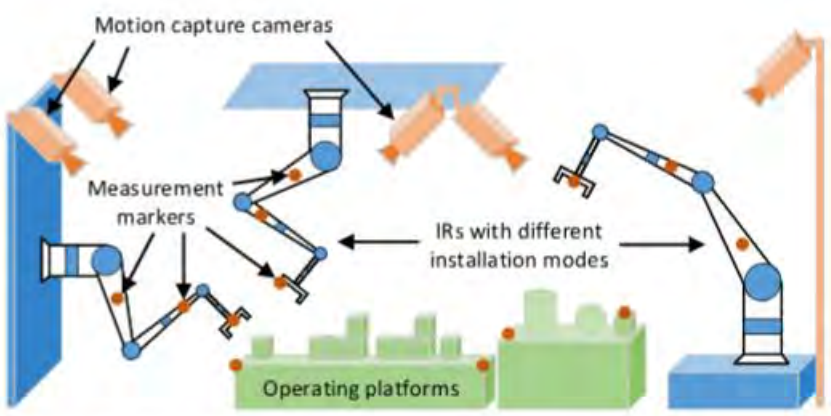

FIG. 1. Calibration of IR kinematic parameters using motion capture systems for multiple IR installation modes.

How NOKOV Contributes to the Research

IV. SIMULATION AND EXPERIMENT
This paper uses both simulation and experimentation to val-idate the proposed method. The IR used for verification is theUniversal Robots UR5. Simulation is employed to demonstrate thecalculation details and explore the impact of various measurementerrors on the algorithm. The method ' s effectiveness is ultimately verified using the real IR and the NOKOV Mars4H motion capture system.

Citation Wang X, Jia W, Cao J. Fast calibration method for industrial robot kinematics based on motion capture system[J]. Review of Scientific Instruments, 2025, 96(7).

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001536336400002

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GeoPF: Infusing Geometry into Potential Fields for Reactive Planning in Non-trivial Environments

Keywords

Reactive Planning, Redundant Robots, Manipu-lation Planning, Motion and Path Planning

Abstract

Reactive intelligence remains one of the cornerstones of versatile robotics operating in cluttered, dynamic, and human-centred environments. Among reactive approaches, potential fields (PF) continue to be widely adopted due to their simplicity and real-time applicability. However, existing PF methods typically oversimplify environmental representations by relying on isotropic, point- or sphere-based obstacle approximations. In human-centred settings, this simplification results in overly conservative paths, cumbersome tuning, and computational overhead -- even breaking real-time requirements. In response, we propose the Geometric Potential Field (GeoPF), a reactive motion-planning framework that explicitly infuses geometric primitives -- points, lines, planes, cubes, and cylinders -- their structure and spatial relationship in modulating the real-time repulsive response. Extensive quantitative analyses consistently show GeoPF's higher success rates, reduced tuning complexity (a single parameter set across experiments), and substantially lower computational costs (up to 2 orders of magnitude) compared to traditional PF methods. Real-world experiments further validate GeoPF reliability, robustness, and practical ease of deployment, as well as its scalability to whole-body avoidance. GeoPF provides a fresh perspective on reactive planning problems driving geometric-aware temporal motion generation, enabling flexible and low-latency motion planning suitable for modern robotic applications.

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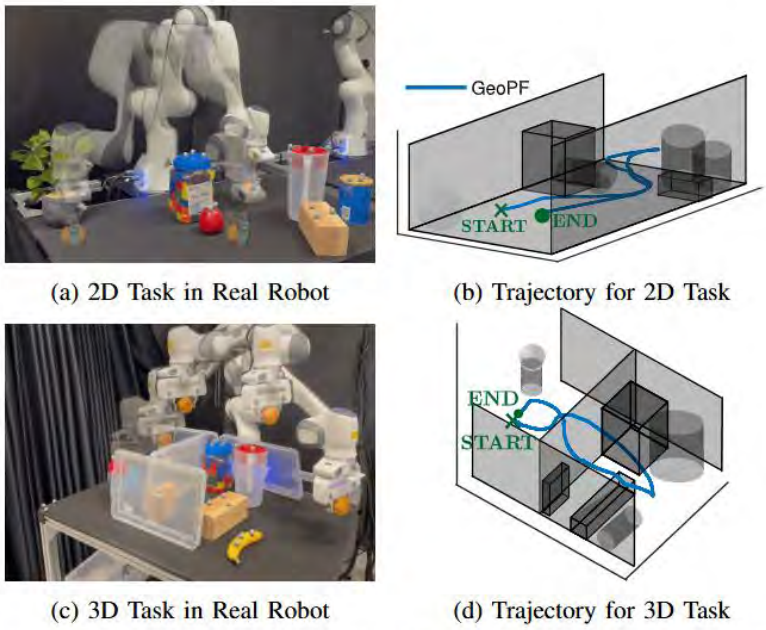

(a) 2D Task in Real Robot (b) Trajectory for 2D Task

(c) 3D Task in Real Robot (d) Trajectory for 3D Task

Fig. 11: Real world experiments. The robot goes from left to right (high-opacity) and then returns, see trajectories (b),(d). The *upper figures* show a 2D tabletop task with multiple obstacles, as lines, cubes, and cylinders. The workspace is shown by planes, w.r.t. the robot's boundaries. The *bottom figures* illustrate a 3D task with four lids representing walls that the robot must avoid during navigation.

How NOKOV Contributes to the Research

To validate GeoPF's practical viability, we deployed it on a 7-DoF Franka Robot. End-effector velocities were generated by mapping the GeoPF forces into joint space via Jacobian pseudoinverse. Obstacles were tracked via a motion capture system (Nokov Mars) and fitted to corresponding geometric primitives. GeoPF was tested across four representative tasks.

Citation Y. Gong, R. Laha and L. Figueredo, "GeoPF: Infusing Geometry Into Potential Fields for Reactive Planning in Non-Trivial Environments," in IEEE Robotics and Automation Letters, vol. 10, no. 11, pp. 11546-11553, Nov. 2025, doi: 10.1109/LRA.2025.3609237.

Link https://ieeexplore.ieee.org/document/11159155

Imitating via manipulability: Geometry-aware combined DMP with via-point and speed adaptation

Keywords

Learning by demonstration, Manipulability ellipsoid, Robot movement skills, Geometry constraints, Velocity adaptation

Abstract

Manipulability ellipsoid on the Riemannian manifold provides an effective criterion for guiding the regulation of robot postures in an efficient and natural manner. While many manipulability-based learning by demonstration (LbD) methods achieve favorable performance in human-like manipulation, the adaptation of movement skills encapsulated in Symmetric Positive Definite (SPD) matrices and the implementation of manipulability-relevant skills related to velocity scaling are still largely open. In this paper, we develop a new framework based on Geometry-Aware Combined Dynamic Movement Primitives (GA-CDMP) for learning movement skills from demonstrations. The GA-CDMP model not only adapts learned trajectories to SPD-via-points but also establishes a correlation between SPD-based trajectories and position trajectories, enabling the adaptation of learned SPD-based trajectories across different non-linear motion velocity scales. The experimental evaluations show that our proposed method exhibits remarkable precision in passing through via-points positioned at a distance from the demonstration, while also substantially improving the invariant shape similarity in manipulability by approximately 65% compared to extended Kernelized Movement Primitives (KMPs). Moreover, our velocity adaptive approach achieves impressive success rates of up to 94% and demonstrates a notable reduction in execution time (11.72 ± 0.45 s), representing an almost 10% decrease in comparison to the state-of-the-art method employed in water-carrying tasks.

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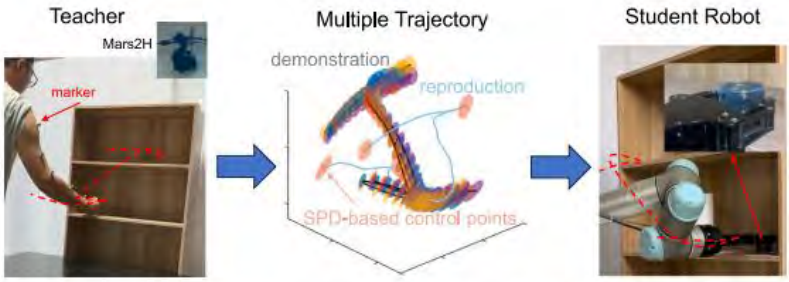

Fig. 1. The UR5 robot imitates human actions by utilizing manipulability to grasp a water-filled cup from one shelf layer and carry it to another.

How NOKOV Contributes to the Research

In this scenario, the human arm can be abstracted as a 7-DOF robotic system, and we employ the NOKOV motion capture system toobtain the joint angles of the human arm. This system includes 8 Mars2H cameras and 7 reflective markers affixed at each joint othe arm, By acurately calculating the marker locations, the motion capture software facilitates the derivation of joint angles for thehuman arm. In the middle of Fig. 1, the black curve represents the demonstration trajectories, and the ellipsoids located on thesetraiectories denote the manipulability ellipsoids of the human arm.

Citation Xu X, Qian K, Zhou B, et al. Imitating via manipulability: Geometry-aware combined dmp with via-point and speed adaptation[J]. Computers and Electrical Engineering, 2024, 117: 109247.

Link https://www.sciencedirect.com/science/article/abs/pii/S0045790624001757

Iterative Pose Estimation for a Planar Object Using Virtual Sphere

Keywords

Planar object; pose ambiguity; optimization Algorithm; local minimum; singular value decomposition;

Abstract

This paper proposed an iterative pose estimation for the planar object to deal with the pose ambiguity in the Perspective n Points (PnP) problem. Specifically, by utilizing the unit virtual sphere, the PnP pose estimation problem can be performed as a minimization of the error function with three independent transitional parameters, referred to as the coupling position. Then, Levenberg-Marquardt (LM) optimization algorithm is applied to acquire the coupling position of the first local minimum. Furthermore, the coupling position is represented as the two Euler angles and the vector length, which are combined with the planar points to compute the second local minimum approximation as the initialization of the second LM algorithm. Consequently, once the global coupling position in the two local minimum is decided by the lower error, the orientation and position are directly decoupled by using the singular value decomposition (SVD). It is shown that the designed pose estimation is able to achieve prescribed performance for locating and distinguishing two local minimum, and meanwhile guarantee the superior computation behavior under the pose ambiguity for the planar object. Finally, numerical simulation and physical experiment are conducted to validate the effectiveness of the proposed method, compared to the state-of-the-art PnP methods.

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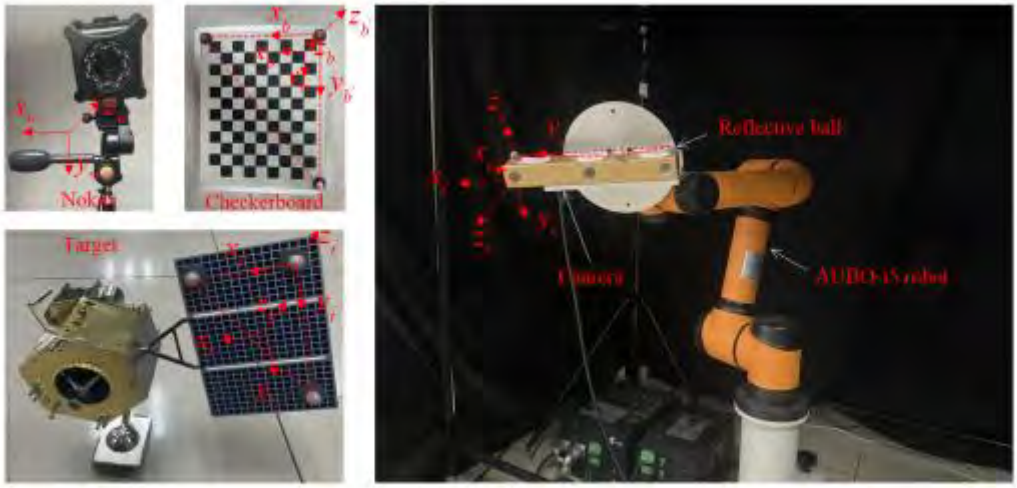

Fig. 10. The composition of the ground experimental system.

How NOKOV Contributes to the Research

To verify the effectiveness of the proposed approach, the ground experimental system is designed, shown in Fig. 10. The experimental system is mainly composed of the Bumblebee camera, the AUBO-i5 robot, the FY 4 target model, the checkerboard, and the Nokov tracker system, wherein seven reference frames are all introduced in Table I. The camera model that is mounted on the end of the robotic arm is applied to acquire the target pictures, while the Nokov tracker system is regarded as the ground truth data.

Citation Jiang C, Hu Q. Iterative pose estimation for a planar object using virtual sphere[J]. IEEE Transactions on Aerospace and Electronic Systems, 2022, 58(4): 3650-3657.

Link https://ieeexplore.ieee.org/abstract/document/9684975

Kinematics Optimization of a Novel Cable-Driven 7-Dof Redundant Manipulator

Keywords

Kinematics analysis; Spherical parallel mechanism; Redundant manipulator; LDWPSO;

Abstract

Redundant manipulators can accomplish complex tasks due to the redundant degree of freedom (DOF). At the same time, their kinematics calculations are complicated. In this study, a hybrid method is proposed to obtain the optimal kinematics solution for a 7-DOF redundant anthropomorphic manipulator. Kinematics analysis of the spherical parallel shoulder joint was performed by using a geometric method and coordinate transformation. Kinematics analysis of the redundant manipulator was performed by a geometric method with an optimizing arm angle. Linearly decreasing weight particle swarm optimization (LDWPSO) was used to optimize the arm angle to minimize the motion time of the manipulator. The kinematics calculation of the shoulder joint was verified by a combination of SolidWorks and MATLAB software. The kinematics calculation of the redundant manipulator was verified by MATLAB. The linear, circular and figure 8-shaped motion trajectories were used to evaluate the proposed method in the simulation. The simulation results showed that the motion time with optimization of the arm angle was only 16%–30% of that without optimization. Furthermore, the proposed method was evaluated through real manipulator experiments, and the experimental results were similar to those in the simulation.

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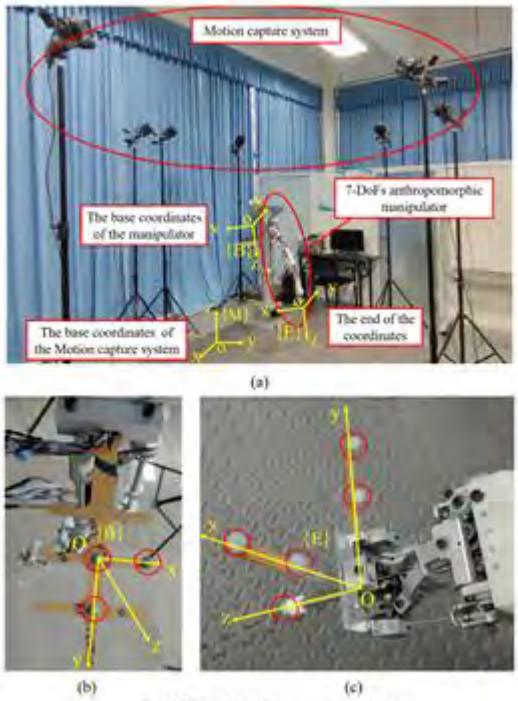

Fig. 22 Kinematics experiment on the manipulator

How NOKOV Contributes to the Research

This section describes an experiment performed to test the kinematics of the whole arm. As shown in Fig. 22, the experimental platform is built. A motion capture system is used to evaluated the manipulator. The motion capture system is composed of eight Mars1.3H infrared high-speed cameras of the NOKOV system, with a resolution of 20481088 and an accuracy of 0.02 mm.

Citation Chen Y, Zhang X, Yanjiang H, et al. Kinematics Optimization of a Novel Cable-Driven 7-Dof Redundant Manipulator[J]. Available at SSRN 4240782.

Link https://www.sciencedirect.com/science/article/abs/pii/S0921889023000167

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Modeling of Human Throwing Motion from Human Demonstration Using a Hidden Markov Model

Keywords

Human Throwing Motion, Feature Vectors, HMM, Motion Sequences

Abstract

In the human-robot interaction, teaching robots to learn human skills is a challenging work. Throwing is a process of projecting an object to a distant target location, and it is usually considered as one of the skills possessed by humans. To enable robots to perform throwing skills, two steps are required: firstly, modeling and outputting the motion sequences of human throwing motion; secondly, transferring the motion sequences to the robotic arm and realizing the throwing skill on the robotic arm. This paper aims to model the motion of human throwing. First of all, raw datas of human throwing motion are obtained through human demonstration. Afterwards, feature vectors are extracted through the analysis of the raw datas. By applying the HMM to train the feature vectors, the model of human throwing motion n λ final has ultimately been finalized. The result shows that our model can effectively describe the behavior of human throwing and generate the motion sequences of human throwing motion.

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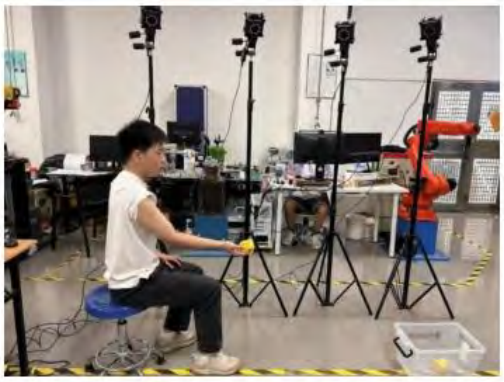

Fig. 1. The experimental site, including a motion capture system, a sandbag and a tagget box.

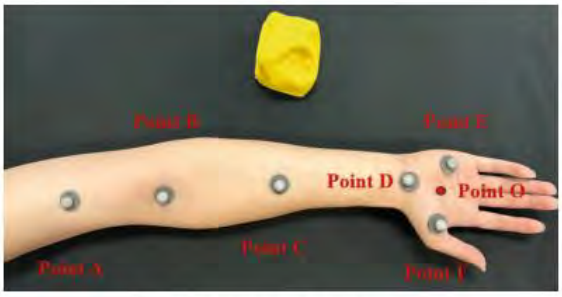

Fig. 2. The location of the markers.

How NOKOV Contributes to the Research

Considering the precision requirement, we employ the NOKOV optical three-dimensional motion capture system, which is designed for high-precision movement tracking, to gather raw data of human throwing. Firstly, we constructed a 4 × 3 m experimental site (see Fig. 1) by utilizing eight Mars1.3H lenses. Subsequently, the aperture and focal length of each lens were meticulously adjusted to enhance the precision of the collected data.

Citation Li S, Huang Y, Zhang X. Modeling of Human Throwing Motion from Human Demonstration Using a Hidden Markov Model[C]//International Conference on Intelligent Robotics and Applications. Singapore: Springer Nature Singapore, 2024: 105-116.

Link https://link.springer.com/chapter/10.1007/978-981-96-0783-9_8

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Noise suppression zeroing neural network for online solving the time-varying inverse kinematics problem of four-wheel mobile manipulators with external disturbances

Keywords

Noise suppression zeroing neural network, Four Mecanum wheeled mobile manipulator, Inverse kinematics, Time-varying disturbance

Abstract

A novel noise suppression zeroing neural network (NSZNN) is presented for the trajectory tracking problem on a four Mecanum wheeled mobile manipulator (FMWMM) by solving its time-varying inverse kinematics (TVIK) problem. The holistic kinematic model of the FMWMM is developed, which can receive synergistic control of the mobile manipulator. Different from the situation without external interference addressed in our previous work, this paper considers a variety of common time-varying interferences by studying the basic principles of various noises, and proves the NSZNN model's of the validity and superiority, which solves the TVIK problem of the FMWMM with external disturbances through theoretical analyses. Compared with the existing gradient neural network (GNN) and the traditional zeroing neural network (ZNN), the most representative hybrid noise is selected to conduct a large number of experiments to substantiate the high efficiency and robustness of the NSZNN model. Finally, the NSZNN model is verified on the FMWMM via a robot operating system (ROS) by a successful execution of the trajectory tracking task.

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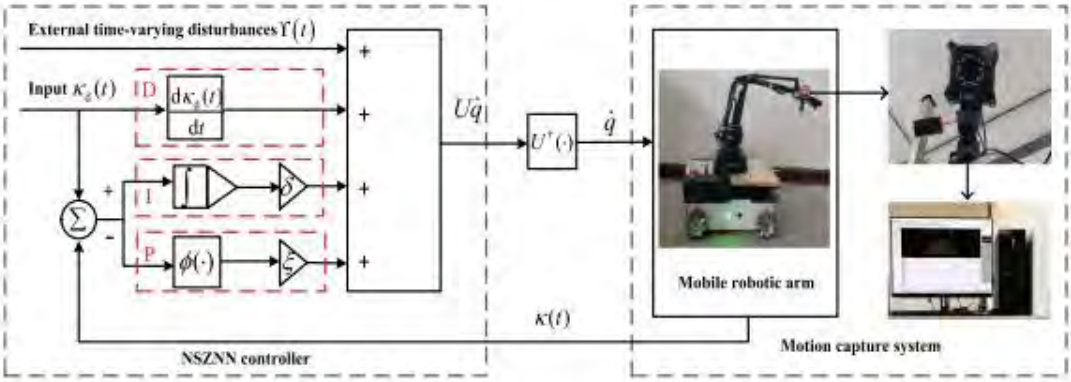

Fig. 14 Algorithm validation schematic block diagram

How NOKOV Contributes to the Research

In order to verify the validity and stability of the NSZNN algorithm, a further test is con.ducted on a physical mobile manipulator. The algorithm verification principle block diagram is shown in Fig. 14. The optical motion capture system produced by NOKOV is used to capture the position of the Marker point (the point in the red circle in Fig. la) of the ROS mobile manipulator's EE in 3D space real-timely.

Citation Sun Z, Zhou Y, Tang S, et al. Noise suppression zeroing neural network for online solving the time-varying inverse kinematics problem of four-wheel mobile manipulators with external disturbances[J]. Artificial Intelligence Review, 2024, 57(8): 211.

Link https://link.springer.com/article/10.1007/s10462-024-10804-4

Performance Evaluation of Optical Motion Capture Sensors for Assembly Motion Capturing

Keywords

Contour error, learning from demonstration, optical motion capture, performance evaluation

Abstract

The optical motion capture (MoCap) sensor provides an effective way to capture human motions and transform them into valuable data that can be applied to certain tasks, e.g. robot learning from demonstration (LfD). In spite of the wide utilization of optical MoCaps in LfD studies, there are few works that explore their potentiality in small parts robotic assembly. Robot manipulation skill learning from demonstration has gained the attention of researchers recently and robotic 3C (Computer, Communication, and Consumer Electronics) product assembly turns out to be a promising application thanks to the increasing consumption of 3C products. To further explore the potential of optical MoCaps in robotic 3C product assembly. This work proposes a performance evaluation protocol that takes the characters of both optical MoCaps and 3C product assembly operations into account. The proposed evaluation protocol includes static and trajectory evaluations. The former refers to the widely used evaluation indicators such as precision and accuracy. Meanwhile, the trajectory evaluation takes contour error as an error metric. Three popular optical MoCaps are studied in the experiment. Experiment results show that the static performance of all of the three optical MoCaps can meet the requirements of the 3C product assembly task. What's more, Prime X41 possesses the best trajectory performance. This work sheds light on the wider usage of optical MoCaps in manufacturing industries.

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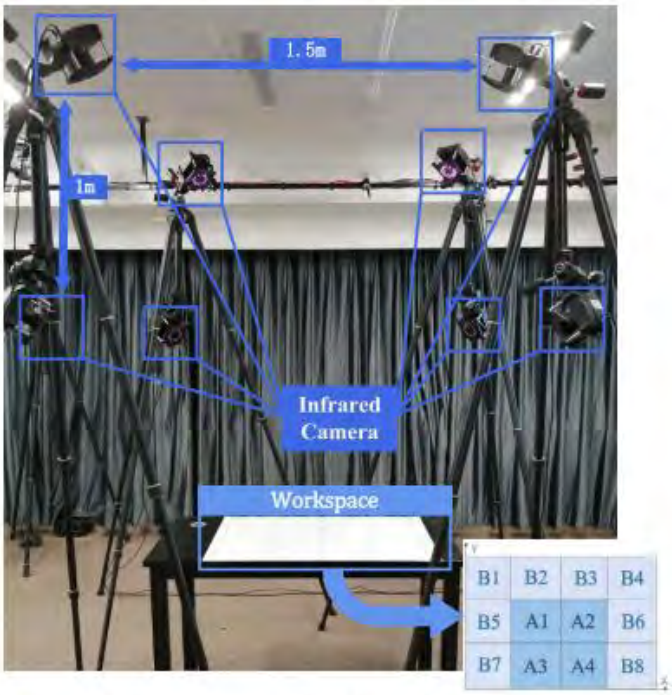

FIGURE 5. **Layout of cameras and test blocks in the workspace.**

How NOKOV Contributes to the Research

Three optical MoCaps including Prime X41, Mars4H, and Vantage V5 (Figure 1) are selected in experiments whose parameters are listed in Table 1. For each set of optical MoCap, eight cameras are placed around the workspace (Figure 5) to let their visual fields cover the workspace as much as possible and save space for practical industrial applications. The eight cameras are installed in two layers and four of them are placed at the four endpoints of the central area in each layer. The distance between the left and right camera in one layer is 1.5m, and that between the upper and lower layer is 1m.

Citation Hu H, Cao Z, Yang X, et al. Performance evaluation of optical motion capture sensors for assembly motion capturing[J]. IEEE Access, 2021, 9: 61444-61454.

Link https://ieeexplore.ieee.org/abstract/document/9408569

Reinforcement Learning and Sim-to-Real Method of Dual-Arm Robot for Capturing Non-Cooperative Dynamic Targets

Keywords

On orbit capture, Reinforcement learning algorithm, Dynamic non-cooperative target

Abstract

The gradual increase of space debris such as invalid satellites poses a great threat to human space exploration activities. Dual-arm robots are increasingly being used in on-orbit capture tasks due to their flexible and stable characteristics. Modeling and controlling a high-dimension dual-arm robot are difficult, and planning a collision-free path for it takes a long time, hence, it's difficult to capture a dynamic non-cooperative target with a dual-arm robot. To address these problems, this paper proposes an intelligent capture algorithm based on the PPO algorithm with the A2C framework, as the reinforcement learning algorithm requires no model of the robot. Collision detection is introduced into the training so that the strategy network obtained from the training does not need real-time collision detection when it's applied to a real robot, namely, it can output relevant control commands in real-time without path planning time. Furthermore, the randomization method improves the generalization ability of the model. The Actor-Networks have been tested in both simulations and on a real robot. The average capture rate is 96.8% in the simulation and a target with rotation speed in the range [−3.0,3.0]∘/s can be caught in the real world, which proves the effectiveness of the intelligent capture algorithm proposed.

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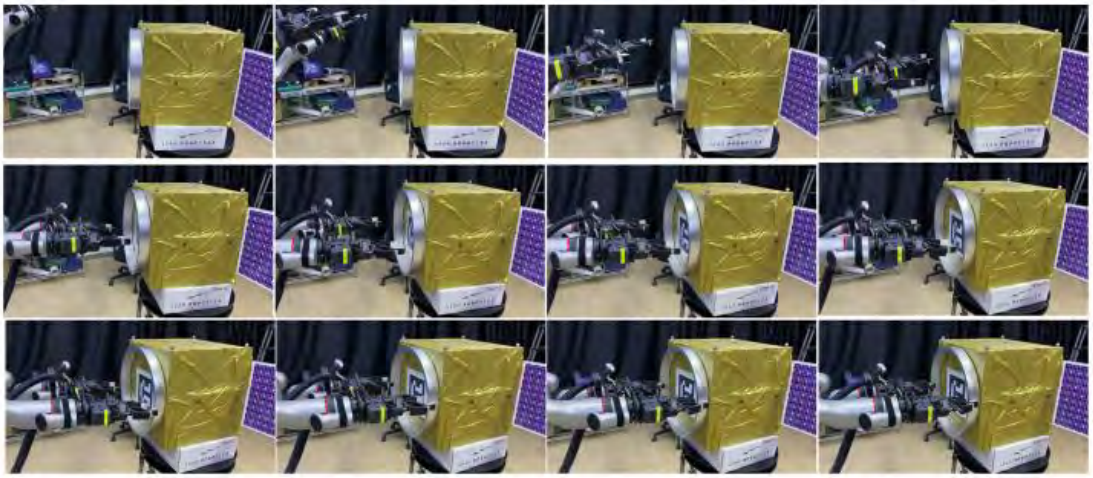

Fig. 5. The capture process with Nokov.

How NOKOV Contributes to the Research

We also used a Nokov motion capture system to obtain the capture points'positions and orientations, as the accuracy and topic publish rate are both higher than the camera, we got a better result that the capturable speed of the targetcan be increased to 3.0°/s. Figure5shows the process of a capture mission,and the rotation speed of the target is 3.0°/s. The total time of the process isapproximately 10 s.

Citation Du W, Li N, Chen Y, et al. Reinforcement Learning and Sim-to-Real Method of Dual-Arm Robot for Capturing Non-Cooperative Dynamic Targets[C]//International Conference on Intelligent Robotics and Applications. Singapore: Springer Nature Singapore, 2023: 270-281.

Link https://link.springer.com/chapter/10.1007/978-981-99-6492-5_24

Robot target tracking control considering obstacle avoidance based on combination of deep reinforcement learning and PID

Keywords

Robot, target tracking, collision avoidance, deep reinforcement learning, trajectory planning

Abstract

When simultaneously addressing the challenges of dynamic target tracking and obstacle avoidance for robots, conventional control and control only based on reinforcement learning cannot deal with the complex scenarios effectively. The purpose of this study is to design a robot control algorithm that combines deep reinforcement learning (Soft Actor-Critic, SAC) with PID to achieve real-time tracking of a moving object and effectively avoid single or multiple obstacles. The control of the robot is divided into two key components: initially, the first joint of the 6-degree-of-freedom robot is controlled by PID algorithm, which makes the working plane (the plane coincident with the axis of the first joint and parallel to the linkage) quickly approach the target until it overlaps. Subsequently, the task of reinforcement learning is simplified to control the planar robot to track the target projection in working plane while avoiding the obstacle projection, ultimately achieve target tracking and obstacle avoidance in 3D space. The simulation and experiment results show that the proposed method has good efficiency and convergence speed. The SAC-PID strategy effectively controls the Universal-Robots UR5 to complete dynamic target tracking while accomplishing obstacle avoidance in both virtual and real-world environments.

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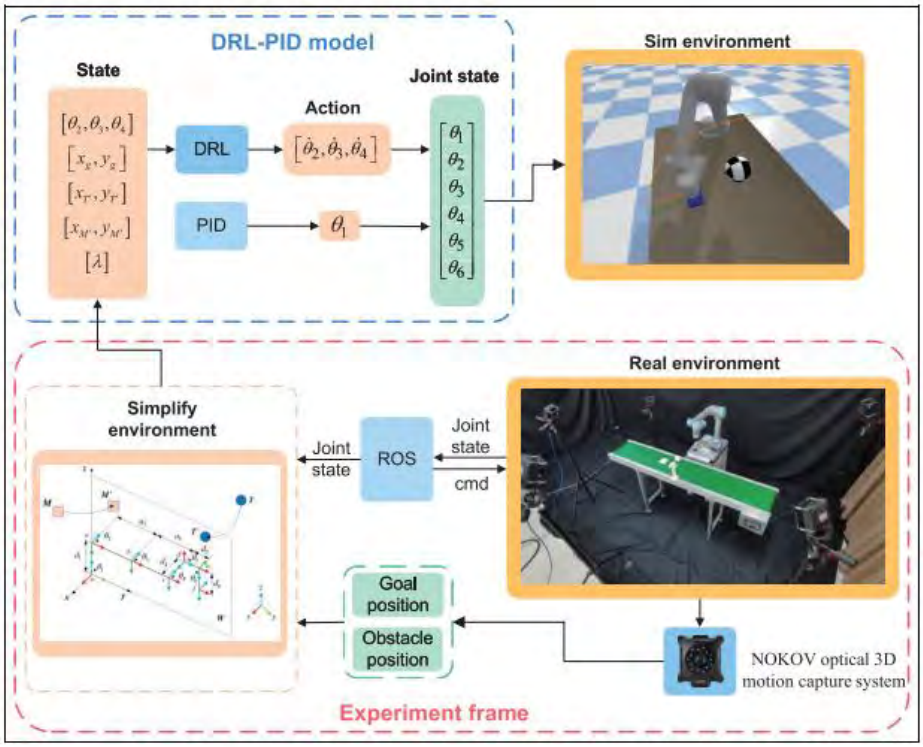

Figure 6. Simulation system framework.

How NOKOV Contributes to the Research

We employ the NOKOV optical 3D motion capture system to capture the positional coordinates of both the target and obsta-cles. This data is then integrated into the control strategy. Simultaneously, we utilize the Robot Operating System (ROS) to facilitate communication with theUR5 robot, enabling motion control and the retrieval of status information.

Citation Liu Y, Jiang X, Li X, et al. Robot target tracking control considering obstacle avoidance based on combination of deep reinforcement learning and PID[J]. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, 2025, 239(3): 550-561.

Link https://journals.sagepub.com/doi/10.1177/09596518241274000

S2SNet: Two-stream geometry-aware sequence to sequence network for robot motion skills learning and generalization

Keywords

Learning-from-demonstration, Multi-type skills learning, Manipulability ellipsoid, Quaternion, Riemannian manifolds, Geometry constraints

Abstract

Pick-and-place manipulation is a pivotal component in many robotic tasks. In unstructured, dynamic and uncertain environments, controllers are required to learn and generalize pick-and-place manipulation from multi-type demonstrations, which are often represented in Euclidean (e.g., position), and non-Euclidean (e.g., quaternion, symmetric positive definite (SPD) matrix) data. While many learning from demonstration (LfD) methods excel in manipulation tasks with single-type data, the adaptation of motion skills across different data types remains largely open. In this paper, we propose a two-stream Sequence-to-Sequence Network (S2SNet) that utilizes multiple tangent spaces to learn motion skills from multi-type demonstrations. The S2SNet is capable of adapting the learned motion skills to different types of waypoints, such as position waypoints, SPD-based waypoints, and quaternion waypoints. Additionally, we introduce a demonstration segmentation operation within S2SNet to enhance its generalization ability across different types of waypoints and to reduce the dependency on a large volume of real demonstrations. Experimental evaluations show that S2SNet outperforms state-of-the-art methods in passing through different types of waypoints. It achieves a reduction in root mean square error (RMSE) of 11%, 70%, and 9% for passing through Euclidean, SPD matrix, and quaternion data, respectively, while preserving the shape features of the demonstration motions.

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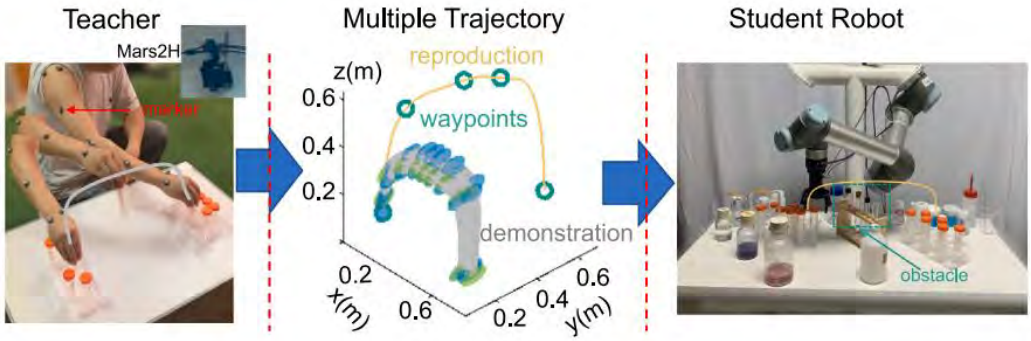

Fig. 12. A UR5 robot imitates a human to transport the test tubes to their designated racks on the chemical workbench.

How NOKOV Contributes to the Research

In this chemical scenario, the human arm can be modeledas a manipulator with seven degrees of freedom, and the motion ofeach joint can be captured using the NOKOV motion capture system.The system utilizes eight Mars2H cameras and seven reflective markers affixed to each joint of the arm. Through the precise calculation of marker locations, the motion capture software generates the join tangles of the human arm.

Citation Xu X, Qian K, Zhou B, et al. S2SNet: Two-stream geometry-aware sequence to sequence network for robot motion skills learning and generalization[J]. Advanced Engineering Informatics, 2024, 62: 102702.

Link https://www.sciencedirect.com/science/article/abs/pii/S1474034624003501

Super twisting and hierarchical sliding mode anti-swing control of boom crane

Keywords

Boom crane, underactuated system, hierarchical sliding mode, second order super-twisting sliding mode algorithm, antiswing control

Abstract

When the multiple mechanisms such as the slewing, luffing, and hoisting mechanisms work together, the boom crane has the strong coupling and underactuated characteristics which make it difficult to prevent the load swing. In this paper, a new dynamic model is established for the boom crane with the cooperative motion, where the kinetic energy and potential energy of the boom pitching motion are added to the Lagrange equation to calculate the driving torque of the luffing cylinder and the rotary mechanism. A super-twisting hierarchical sliding mode control method is proposed. The equivalent control law is obtained by a second-order sliding mode surface constructed with the driving and underactuated part, and the switching control law is designed by a second-order super-twisting sliding mode algorithm to suppress the chattering. The stability of the system is proved by Lyapunov function. The simulation and experiment results show that accurate anti-swing and strong robustness are achieved, and the system performance is significantly improved.

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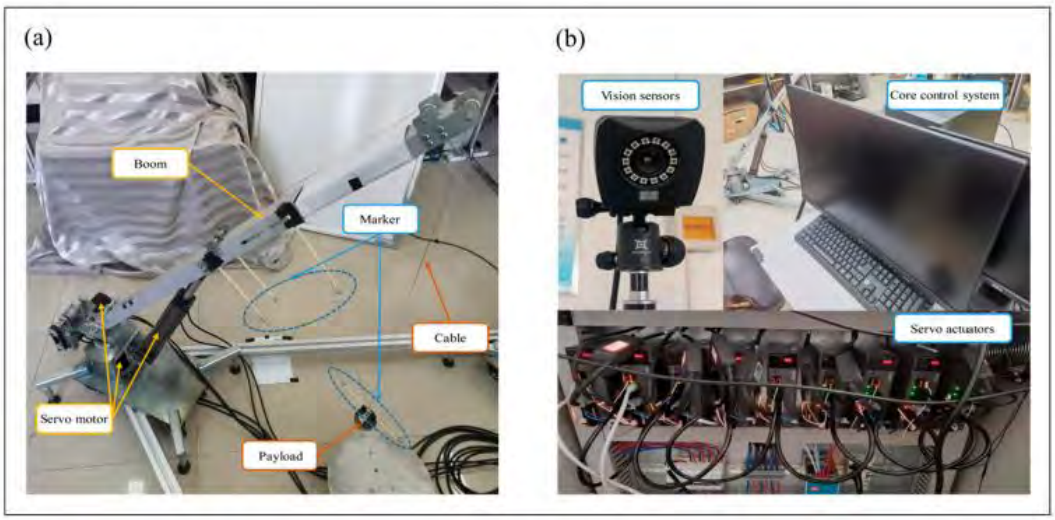

Figure 10. Prototype of the boom crane. (a) Boom crane. (b) Sensors and controllers.

How NOKOV Contributes to the Research

The structure of the experimental prototype is illustratedinFigure 10.In the experiment, the NOKOV motion capture camera isused to collect parameters of the crane and payload. Then, the camera communicates with the host computer through UDP (user datagram protocol) to send coordinates.

Citation Chen Z, Geng J, Wang Z, et al. Super twisting and hierarchical sliding mode anti-swing control of boom crane[J]. Journal of Vibration and Control, 2024: 10775463241288952.

Link https://journals.sagepub.com/doi/abs/10.1177/10775463241288952

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Trajectory Prediction Method of Flying Uneven Object Based on Improved Informer

Keywords

Trajectory prediction, Uneven object, Human-computer interaction, Deep learning, Informer

Abstract

Trajectory prediction of moving objects in flying state is an important technology involved in a large number of human-computer interaction tasks. Because uneven objects are easily affected by air resistance, Magnus effect and other factors in flight, it is difficult to carry out force analysis and realize exact trajectory prediction based on physical modeling. To solve these problems, we proposed a trajectory prediction method based on deep learning neural network. Multi-dimensional feature data of uneven flying object trajectory was collected by optical motion capture device, then an informer model was built to predict long-term sequence data. The model can effectively reflect the changing trend of the motion state of the object during flying and obtain the variable length pose data by model output. At the same time, we propose a valid method to optimize the structure of model, which can effectively lightweight the attention module in the encoder and decoder, change model generation mode to rolling output and improve the computing speed and accuracy of our model. Finally, we verified the improved model performance on the NMP public dataset, the experimental results show that our improved model has a better prediction effect than the original model and other methods such as Long Short-Term Memory network and Sequence to Sequence neural network. It gets an improvement in error accumulation which reduce 0.017 in MAE, 0.005 in MSE and 0.173 in MAPE compared to original model and has a good generalization performance in prediction task of other objects.

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Fig. 2. Dynamic capture hardware environment

How NOKOV Contributes to the Research

The space size of the optical motion capture system we built is 3m×3m×2.2 m,and the environment layout is shown in Fig.2. High-performance infrared lenses of NOKOV series are used. The principle of data acquisition is to establish a rigid body model of an object by identifying and acquiring the pasted reflection points on the surface of the object, so as to achieve real-time recording of the pose information during the movement of the model.

Citation Wang Z, Huang Y, Zhang X. Trajectory Prediction Method of Flying Uneven Object Based on Improved Informer[C]//International Conference on Intelligent Robotics and Applications. Singapore: Springer Nature Singapore, 2024: 231-242.

Link https://link.springer.com/chapter/10.1007/978-981-96-0774-7_17

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Unifying Obstacle Avoidance and Tracking Control of Redundant Manipulators Subject to Joint Constraints: A New Data-Driven Scheme

Keywords

Data-driven control, obstacle avoidance (OA), redundant manipulator, zeroing neural network (ZNN)

Abstract

In modern manufacturing, redundant manipulators have been widely deployed. Performing a task often requires the manipulator to follow specific trajectories while avoiding surrounding obstacles. Different from most existing obstacle-avoidance (OA) schemes that rely on the kinematic model of redundant manipulators, in this article, we propose a new data-driven obstacle-avoidance (DDOA) scheme for the collision-free tracking control of redundant manipulators. The OA task is formulated as a quadratic programming problem with inequality constraints. Then, the objectives of obstacle avoidance and tracking control are unitedly transformed into a computation problem of solving a system including three recurrent neural networks. With the Jacobian estimators designed based on zeroing neural networks, the manipulator Jacobian and critical-point Jacobian can be estimated in a data-driven way without knowing the kinematic model. Finally, the effectiveness of the proposed scheme is validated through extensive simulations and experiments.

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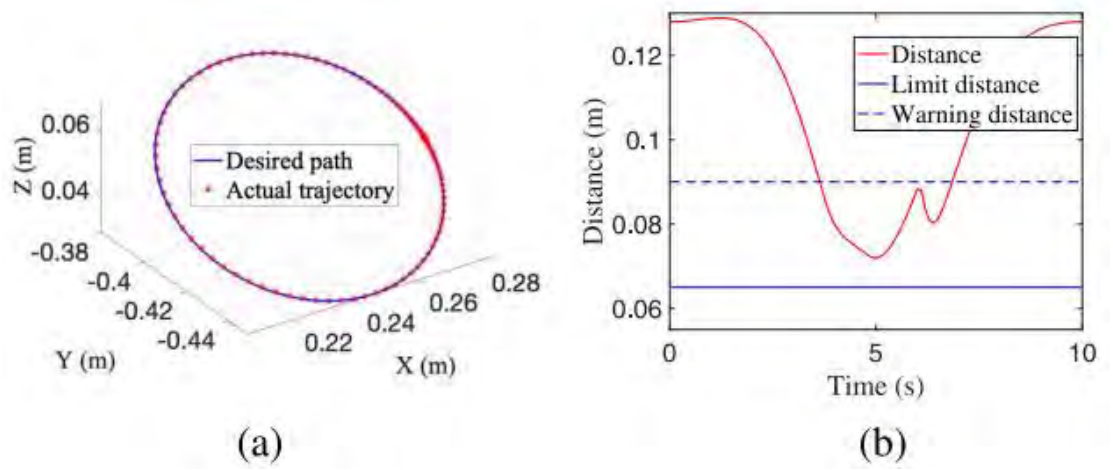

How NOKOV Contributes to the Research

For the Jacobian estimators, the feedback signals including position, velocity, and acceleration are necessary. This information could be accurately acquired in real-time through existing mature devices. For example, the NOKOV Motion Capture System can provide this information at a frequency of 60 Hz. The MicronTracker H3-60 can also measure the position information with the accuracy being 0.2 mm at a frequency of 16 Hz.

Citation Yu P, Tan N, Zhong Z, et al. Unifying Obstacle Avoidance and Tracking Control of Redundant Manipulators Subject to Joint Constraints: A New Data-Driven Scheme[J]. IEEE Transactions on Cognitive and Developmental Systems, 2024, 16(5): 1861-1871.

Link https://ieeexplore.ieee.org/abstract/document/10497180

Vision-based Autonomous Detecting and Grasping Framework for the Fully-actuated Aerial Manipulator

Keywords

YOLO, Three-dimensional displays, Target recognition, 3-DOF, Grasping, Detectors, Manipulators

Abstract

The Aerial Manipulator (AM) combines the flexibility of aerial platforms with the manipulative capability of manipulators. Autonomous grasping of the AM poses challenges due to its complex kinematics/dynamics and target object pose acquisition. This paper introduces a fully-actuated AM which consists of a fully-actuated hexarotor and a 3-DoF manipulator. The fully-actuated aerial platform provides a more stable view for the camera during the AM motion. The feedback linearization controller is used in the aerial platform to ensure the stability of the AM during the motion of the manipulator. The YOLO v5 object detector combines the Oriented Bounding Box (OBB) to form a rotating object detector which can identify the target object and obtain its tilt angle. Combined with the depth camera, the position of the target object in three-dimensional (3D) space can be obtained. Within the working space, the manipulator performs autonomous planning and grasping according to the position and tilt angle of the target. Experimental demonstrates the performance of the proposed AM system.

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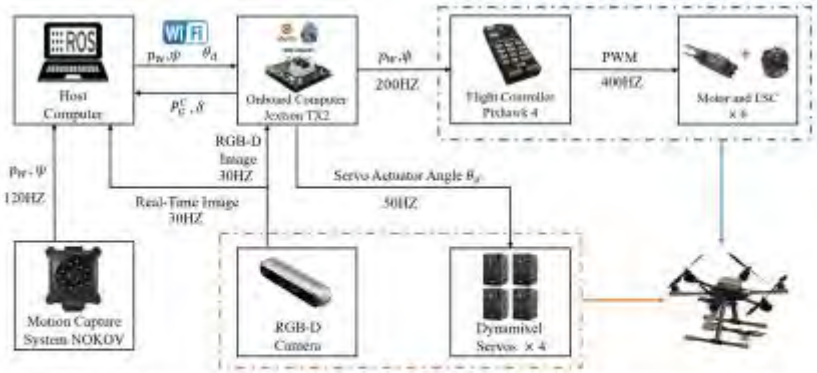

Fig. 5: Diagram of important coordinate frames of the proposed AM.

How NOKOV Contributes to the Research

The positionp Wand yawψ of the aerial platform are acquired by NOKOV motion capture system, and the pitch and roll areacquired by the built-in IMU in Pixhwak 4.

Citation Hao S, Song G, Gu Y, et al. Vision-based autonomous detecting and grasping framework for the fully-actuated aerial manipulator[C]//2023 IEEE International Conference on Robotics and Biomimetics (ROBIO). IEEE, 2023: 1-6.

Link https://ieeexplore.ieee.org/abstract/document/10354730

Vision-based human–robot object handover in dynamic environments: a safety-aware framework with real-time anthropomorphic planning

Keywords

Human – robot object handover, Human – robot interaction, Hand segmentation, Motion capture, Anthropomorphic motion trajectories

Abstract

Purpose – Dynamic human–robot object handover faces challenges such as insufficient generalization capability, limited real-time performance and safety concerns in practical applications. This paper aims to propose a vision-based human–robot object handover system to execute object handovers from a human worker to a robot more safely, efficiently and fluently in dynamic scenarios.

Design/methodology/approach – The proposed system takes images captured by a single RGB-D camera to complete object handover scene understanding. Putting a high emphasis on efficiency and safety, a novel lightweight EMA-UNet network is designed for efficient and high-precision hand segmentation and GR-ConvNet network is used for grasp detection. To maximize fluency of human–robot object handover, an anthropomorphic trajectory planning method based on dynamic movement primitives (DMPs) is used in this system. Experiments were conducted on the AUBO E5 robotic arm platform, with system performance validated through 200 handover tasks performed by five participants.

Findings – The experimental results show that the system achieves an average handover success rate of 84% across diverse objects, with a 1% probability of collision. Compared with U-Net network, the proposed EMA-UNet network reduces the number of parameters by 98.5% while maintaining an IoU of 98.04%. The system's inference time is 0.16 s, which can meet real-time requirements in dynamic human–robot object handover.

Originality/value – In this work, a vision-based human–robot object handover system is proposed by combining lightweight hand segmentation, multimodal grasp detection and DMP-based trajectory planning. The results demonstrate that the proposed system can facilitate a dynamic, efficient, safe and fluent human–robot object handover.

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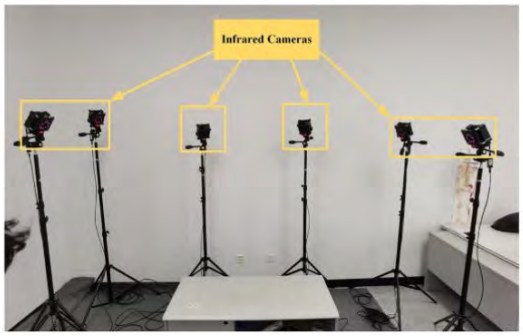
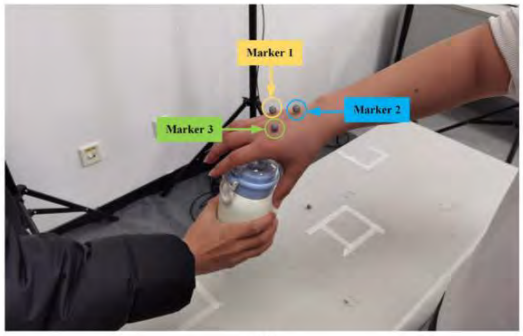
Figure 4 Optical motion capture platform



(a)



(b)

How NOKOV Contributes to the Research

The demonstration data used in this work is obtained by an optical motion capture platform provided by Nokov Science \&Technology Cooperation Ltd. (NOKOV, 2025)that tracks three reflective markers pasted on the operator's hand, as shown in Figure 4(b). The motion capture system is used to accurately record the human hand's motion character is ticsduring object handover, providing reliable data for generatingnatural and smooth robotic trajectories. During the execution of an object handover task, once the grasp position of the targetobject has been determined, the DMP model is used togenerate an anthropomorphic motion trajectory from the initialstate to the handover endpoint. This DMP-based trajectorygeneration approach not only ensures the smoothness andnaturalness of the robot's motion path but also enables onlineadjustments and task generalization, adapting to different object positions and dynamic target requirements.

Citation Zhao H, Zou Y, Zhang J. Vision-based human–robot object handover in dynamic environments: a safety-aware framework with real-time anthropomorphic planning[J]. Industrial Robot: the international journal of robotics research and application, 2025.

Link https://www.emerald.com/ir/article-abstract/doi/10.1108/IR-04-2025-0142/1294071/Vision-based-human-robot-object-handover-in?redirectedFrom=fulltext

Whole-Body Integrated Motion Planningfor Aerial Manipulators

Keywords

Aerial manipulator, delta arm, motion planning,collision avoidance, waypoint constraint

Abstract

Expressive motion planning for Aerial Manipulators (AMs) is essential for tackling complex manipulation tasks, yet achieving coupled trajectory planning adaptive to various tasks remains challenging, especially for those requiring aggressive maneuvers. In this work, we propose a novel whole-body integrated motion planning framework for quadrotor-based AMs that leverages flexible waypoint constraints to achieve versatile manipulation capabilities. These waypoint constraints enable the specification of individual position requirements for either the quadrotor or end-effector, while also accommodating higher-order velocity and orientation constraints for complex manipulation tasks. To implement our framework, we exploit spatio-temporal trajectory characteristics and formulate an optimization problem to generate feasible trajectories for both the quadrotor and manipulator while ensuring collision avoidance considering varying robot configurations, dynamic feasibility, and kinematic feasibility. Furthermore, to enhance the maneuverability for specific tasks, we employ Imitation Learning (IL) to facilitate the optimization process to avoid poor local optima. The effectiveness of our framework is validated through comprehensive simulations and real-world experiments, where we successfully demonstrate nine fundamental manipulation skills across various environments.

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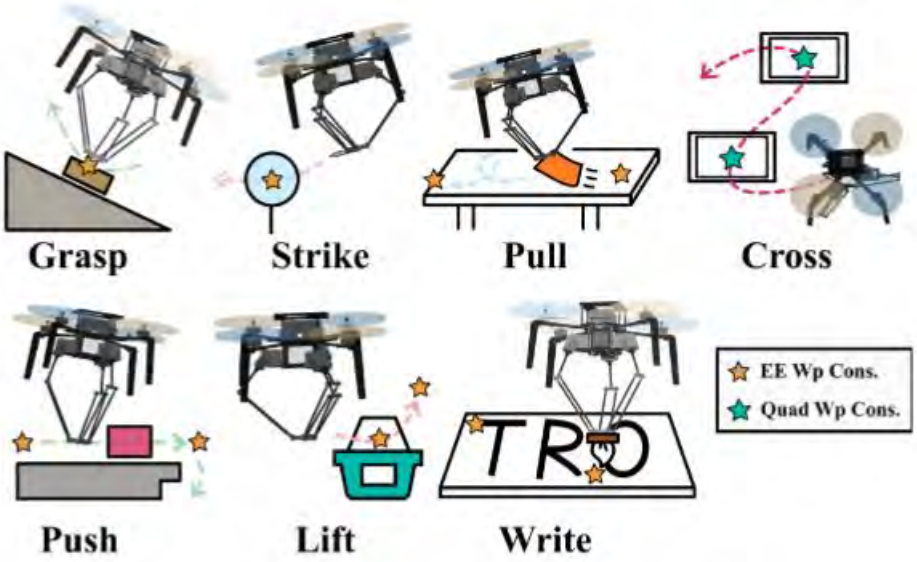

Fig. 6. Illustration of representative manipulation primitives achieved through waypoint constraints. The figure demonstrates various fundamental skills including *Grasp*, *Strike*, *Pull*, *Cross*, *Push*, *Lift*, and *Write*. All these manipulation tasks can be effectively accomplished by implementing appropriate waypoint constraints combined with motion restrictions during execution.

How NOKOV Contributes to the Research

As illustrated in Figure \[3] the experimental platform integrates an NVIDIA Jetson Orin NX 16GB as the onboard computer and an NxtPX4v2 flight controller on a quadrotor equipped with a delta arm. The delta arm utilizes three DYNAMIXEL XL430-W250-T servo motors and features a needle end-effector for precise manipulation tasks. For state estimation, the system employs an Extended Kalman Filter (EKF) that fuses data from the NOKOV Motion Capture System and an onboard IMU.

Citation Deng W, Chen H, Ye B, et al. Whole-body integrated motion planning for aerial manipulators[J]. arxiv preprint arxiv:2501.06493, 2025.

Link https://arxiv.org/abs/2501.06493

Tower-crane robotic arm bolting system for modular integrated construction

Keywords

Modular integrated construction; Construction robotics; Crane-suspended robotic arm; Robotic bolting

Abstract

Modular Integrated Construction (MiC) shifts construction off-site, but on-site bolting of steel module connections remains hazardous and manual. This paper presents Tower-Crane Robotic Arm Bolting System (T-CRABS), an automation system that repurposes the tower crane, a ubiquitous site asset, to deploy a suspended robotic arm. This approach overcomes the payload and access limitations of aerial or ground robots in cluttered workspaces. The contributions to construction automation are threefold: (1) a system design that enables robotic bolting operations by leveraging existing site infrastructure without occupying floor space; (2) a kinetostatic model that captures center-of-gravity shifts during arm motion, providing accurate predictions of platform tilt essential for stable bolting in construction site conditions; and (3) a thrust-based active damping controller that ensures robust pose stabilization during bolting without energy-intensive levelling. Laboratory validations confirm effective swing suppression, robust disturbance rejection with low thrust utilization, repeatable accuracy, and successful bolting. T-CRABS provides a practical path to automate critical MiC assembly, extending robotic automation from factory to construction site.

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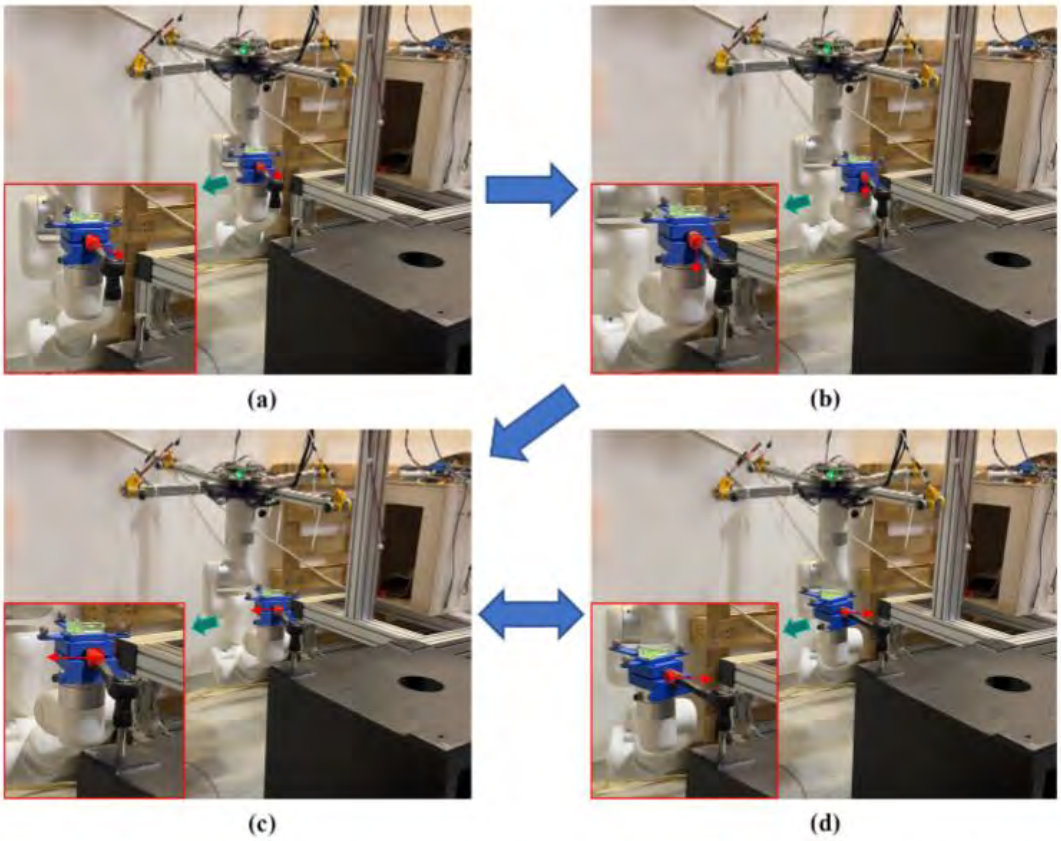

Fig. 22. T-CRABS bolting sequence: (a) approach, (b) fine alignment, (c) engagement, (d) bolting.

How NOKOV Contributes to the Research

A NOKOV optical motion-capture system records the end effector's position, enabling direct comparison with the kinematic model. To maximise inertial disturbances, the arm moves between poses at high speed, challenging the active damping controller.

Citation Jiang R, Li X, Sun S, et al. Tower-crane robotic arm bolting system for modular integrated construction[J]. Automation in Construction, 2026, 187: 106933.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001738505800001

Humanoid Five-Digit Robotic Grasping via Multi-Agent Reinforcement Learning With Potential-Guided Optimization and Weight Scheduling

Keywords

Grasping; Robots; Robot kinematics; Hands; Trajectory; Reinforcement learning; Service robots; Humanoid robots; Thumb; Heuristic algorithms; Multi-agent systems; reinforcement learning; demonstration learning; robotic grasping

Abstract

Dexterous multi-finger robotic grasping faces two primary limitations: 1) traditional demonstration-based learning requires a separate trajectory to be trained for each object type, resulting in limited generalization across different objects; and 2) single-agent reinforcement learning struggles to coordinate the asynchronous motions of the thumb and fingers with heterogeneous joints, leading to inefficient exploration and slow convergence. To overcome these limitations, this study proposed two core innovations, including 1) a dynamic modulation kernel movement primitive (DM-KMP) algorithm, which combines dynamic movement primitives with kernel-based movement primitives to preserve trajectory topology and local probabilistic modulation characteristics; and 2) a novel potential-guided weight scheduling multi-agent deep deterministic policy gradient method (PWS-MADDPG), in which the thumb and fingers are modeled as independent agents. This enables the generation of grasping trajectories for diverse object categories using only a limited number of demonstrations. By leveraging a potential field model to optimize action selection, this method accelerates model convergence. Moreover, a multi-modal reward function with weight scheduling was designed to facilitate a seamless transition from individual optimization to coordinated team behavior. Experiment results demonstrated that the proposed PWS-MADDPG achieved a grasping success rate of 85.48% on a dexterous hand grasping across 11 object categories, outperforming the existing approaches-with a 40.31% improvement over the DDPG algorithm and a 20.05% improvement over the MADDPG algorithm. Furthermore, to verify the grasping stability and adaptability of the system in real-world scenarios, a grip-force validation experiment was designed using a custom cylindrical apparatus embedded with five six-axis sensors. These results demonstrate that the robotic hand using this novel method can maintain stable grasping and adaptively regulate grip and load forces in response

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to incremental external loads, based on a control policy that is trained in both simulation and real-world environments. These findings suggest that this method has strong Sim-to-Real transferability, biological plausibility in force adjustment, and robustness to environmental disturbances, enhancing both the training efficiency and generalization in simulation, and demonstrating high grasping robustness and successful rates in the real-world tasks. The proposed method holds strong potential for high-precision, safety-critical applications, including intelligent manufacturing, prosthetic control, and living assistance. Note to Practitioners-Dexterous robotic grasping is one of the most important demands in industrial manufacturing and home-based services. Traditional robotic grasping methods rely on predefined rules and precisely modeled objects with only two or three digits, thereby being confined in structured environments with well-described grasping objects and standardized grasping programs. It is still a challenging issue to control a robotic hand (unless otherwise specified, the terms humanoid five-digit robotic hand and robotic hand refer to the same platform) with humanoid five digits for dexterous grasping in unstructured environment where the physical characteristics of objects, including shape, weight, and material, as well as the grasping parameters such as joint angles, finger positions, and applied forces, are unknown or difficult to model in advance.\n\nThis study aimed to propose a novel control method enabling a humanoid five-digit robotic hand to grasp diverse objects with high grasping accuracy and adaptability. This novel method features two key innovations: first, it incorporates a learning-from-demonstration mechanism that allows generalization from a small set of expert demonstrations to a broader range of object types; second, it enhances the autonomous learning process of the robotic hand by improving the coordination of multiple fingers, thereby enabling more stable and adaptive grasps in the presence of external disturbances. In practice, this novel method would play a role in control of humanoid five-digit robotic hand with appropriate kinematic (e.g. the attitude and position of each digit) and kinetic (e.g. the force applied by each digit) parameters for grasping a previously unseen object whose physical properties are unknown. This novel method has strong environmental adaptability and autonomous learning, and could be potentially applied in multiple industrial and home-based scenarios.

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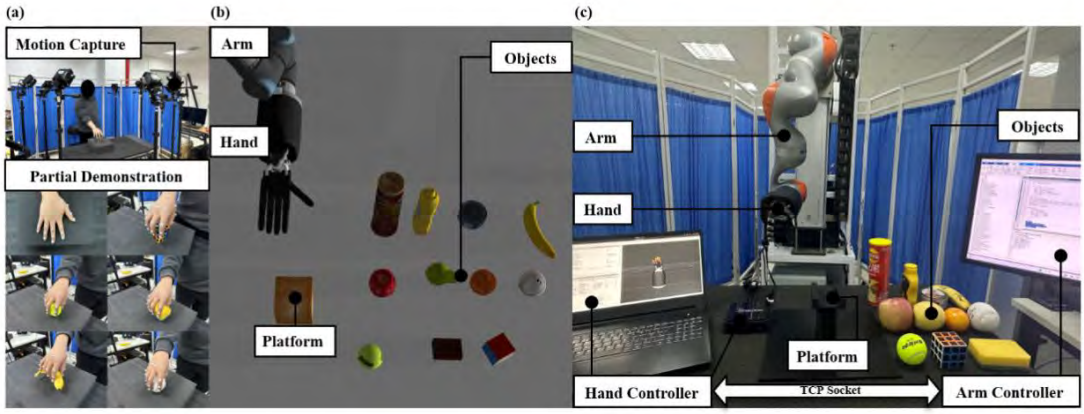

Fig. 2. Experimental set-up. (a) Demonstration. (b) Simulation environment. (c) Real-world environment.

How NOKOV Contributes to the Research

Fig. 2(a) depicts the demonstration phase, where an optical motion capture system (NOKOV Motion Capture System) is employed to record 3D trajectories of human grasping behavior in a natural way. High-precision joint motion data are collected via markers attached to finger joints, and the corresponding joint angle trajectories are obtained through post-processing. A subset of grasping demonstration samples are shown in Fig. 2(a). These samples are representative grasping sequences that can be used to initiate the grasping action and induce the early-stage learning strategies, thereby accelerating the convergence for learning.

Citation Wang J, Li K, Wang X, et al. Humanoid Five-Digit Robotic Grasping via Multi-Agent Reinforcement Learning With Potential-Guided Optimization and Weight Scheduling[J]. IEEE Transactions on Automation Science and Engineering, 2026.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001719519600018

Research on cutting tracking control of tunnel boring machines based on two-layer fuzzy adaptive backstepping method

Keywords

Roadheader; Pose detection; Trajectory tracking control; Self-positioning cutting

Abstract

This paper proposes a novel self-positioning cutting control strategy for tunnel boring machines (TBMs), integrating modern computer vision and deep learning technologies to achieve precise cutting control of the TBM under different working conditions. By using monocular vision technology combined with deep learning algorithms, a method for detecting the six-degree-of-freedom pose of the TBM was developed, which can monitor and calculate the pose changes of the TBM in complex environments in real time. To achieve automatic adjustment and precise control during the cutting process, a two-layer fuzzy adaptive backstepping control method with specified performance is proposed. This control method combines the nonlinear processing ability of fuzzy control with the precise adjustment characteristics of adaptive back-stepping control, enabling efficient real-time adjustment of the TBM's actions in complex and dynamic working environments, ensuring the precision and stability of the cutting process. In addition, the study applied this control strategy to the cutting head trajectory tracking control experiment under different body poses of the TBM. In the experiments, the TBM performed cutting head trajectory tracking control under two different body poses, verifying the applicability and reliability of the method. The experimental results show that, under these two body poses, the maximum contour errors of the cutting head were 42 mm and 45 mm, with errors of approximately 3.51 % and 3.79 %, respectively. These results demonstrate that the proposed self-positioning cutting control method for the TBM can effectively control cutting accuracy in practical applications and has high engineering practical value.

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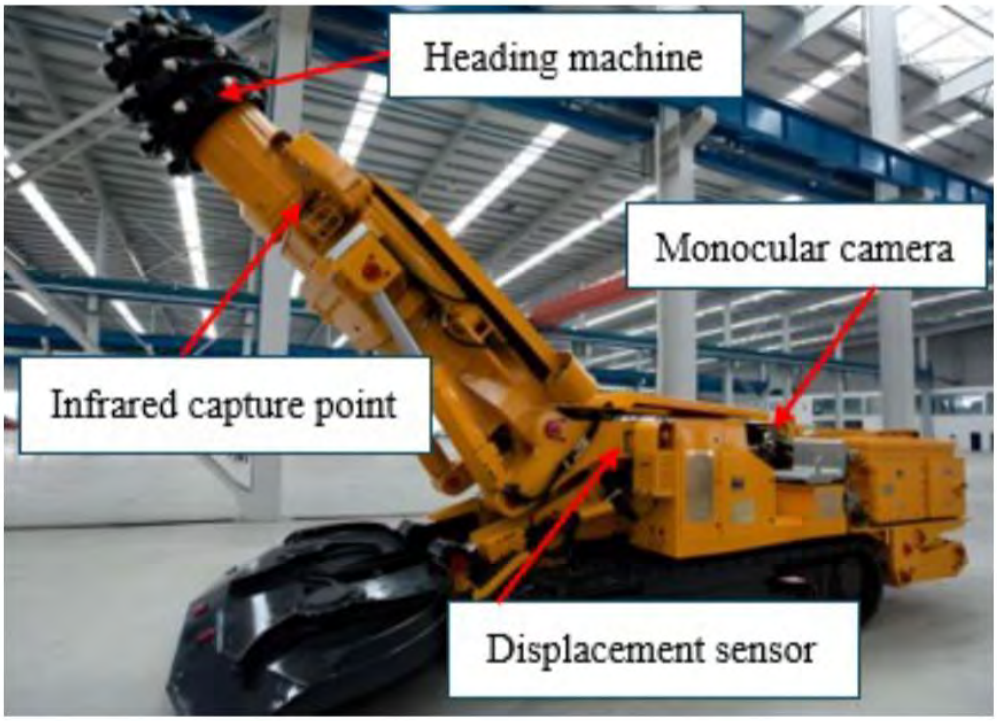

Fig. 7. Integrated experimental system.

How NOKOV Contributes to the Research

The working principle of the NOKOV infrared motion capture system is as follows: The motion capture camera emits infrared light of a specific wavelength, and the motion capture reflective nodes reflect the infrared light back to the camera. Through signal processing and image processing, the two-dimensional coordinates of the node in the camera are obtained. Multiple motion capture nodes are arranged on a rigid body to capture the pose of the rigid body in real time. Therefore, by observing and locating specific nodes with multiple motion capture cameras, the spatial position of the nodes can be obtained. The tunneling machine experimental platform is placed outdoors, and the infrared light in daylight interferes with the infrared motion capture camera. Therefore, it is best to use the infrared motion capture system at night.

Citation Wu H, Ma Y. Research on cutting tracking control of tunnel boring machines based on two-layer fuzzy adaptive backstepping method[J]. Journal of Mechanical Science and Technology, 2026, 40(4): 3063-3077.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001735983000001

Handedness-aware motion mapping for human-robot teleoperation via meta-motion alignment and trajectory reconstruction

Keywords

Teleoperation; Handedness; Human-robot collaboration; Motion mapping

Abstract

Human-robot teleoperation supports remote assistance, maintenance, and rapid changeovers in high-mix low-volume manufacturing. It is crucial for flexible assembly cells, especially during remote rework assistance, rapid changeovers and skill learning. However, inherent human handedness induces asymmetric bimanual motions in practical teleoperation. This asymmetry degrades non-dominant-hand (NDH) efficiency and trajectory quality during frequent hand switching. To address this issue, a handedness-aware motion mapping (HAMM) framework is proposed. Rather than directly replicating operator motions, HAMM reshapes NDH execution toward dominant-hand (DH) motion characteristics under explicit semantic constraints. A handedness-conditioned multi-stage temporal convolutional network (HMTCN) performs stable online meta-motion parsing, enabling motions from both hands to share a unified semantic representation. Conditioned on these semantics, a handedness-aware conditional variational auto-encoder (HA-CVAE) projects NDH trajectories in the dynamic movement primitive parameter space toward a dominant-hand-style distribution. This mapping preserves task intent while improving execution consistency in assembly operations. Experimental results on representative industrial assembly tasks demonstrate that the framework improves the meta-motion recognition accuracy of NDH motions by 8.81% and reduces task completion time by approximately 20%. These findings demonstrate the potential of explicit handedness-aware motion mapping to enhance teleoperation performance, and provide empirical evidence supporting the development of scalable industrial human-robot collaboration and data-efficient skill transfer in human-centered manufacturing systems

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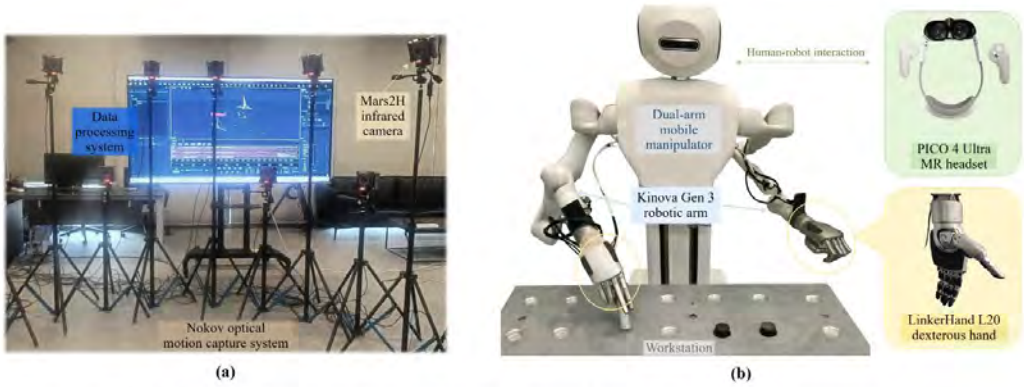

Fig. 8. Experimental platform: (a) human motion capture system and (b) teleoperation and robot execution system.

How NOKOV Contributes to the Research

Human motion capture system. As illustrated in Fig. 8(a), a Nokov optical motion capture system is used with 12 Mars2H infrared cameras operating at 90 Hz. Reflective markers are attached to the operator's wrists, elbows, and key finger joints. The system records three-dimensional trajectories of six markers on each arm while subjects perform representative assembly actions within a 2.5 m by 2.5 m by 2 m workspace.

Citation Tao Y, Wan J, Fu W, et al. Handedness-aware motion mapping for human-robot teleoperation via meta-motion alignment and trajectory reconstruction[J]. Journal of Manufacturing Systems, 2026, 86: 1202-1228.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001760645000001

堆垛机器人末端轨迹精确跟踪控制研究

关键词

堆垛机器人试验平台；动力学方程；LuGre 摩擦模型；自适应双模糊反演滑模器；末端轨迹

摘要

堆垛机器人作为木门制造行业中最为关键的堆垛设备之一，其工作性能直接影响木门制造效率和自动化程度。木门产品定制化和多样化对堆垛机器人末端定位精度提出更高的要求，而末端轨迹精确跟踪可以有效提高定位的精度，避免搬运堆垛时损坏。基于此，本文在简化高速重载堆垛机器人基础上，采用理论仿真和试验验证相结合的方法，开展堆垛机器人末端轨迹跟踪控制研究，以期实现堆垛机器人末端轨迹高精度控制。

根据高速重载机器人的结构和尺寸特点，设计并搭建了堆垛机器人试验平台；采用改进型 D-H 参数法，建立堆垛机器人试验平台运动学模型，获得了堆垛机器人试验平台的末端位置与各关节变量间的关系；利用代数求解法进行逆运动学分析，通过螺旋轨迹验证逆解的精度和可靠性；基于拉格朗日方法，开展了堆垛机器人试验平台动力学研究。研究结果为堆垛机器人试验平台末端轨迹跟踪控制奠定了基础。

为消除堆垛机器人试验平台中存在的关节摩擦力，引入 LuGre 摩擦模型，采用遗传算法和两步动态响应法，对 LuGre 摩擦模型静态参数和动态参数进行辨识；基于 LuGre 摩擦模型前馈补偿策略，设计摩擦状态观测器对关节摩擦力进行在线估计。结果表明其可以有效地减小了关节摩擦力对于堆垛机器人试验平台跟踪轨迹控制性能的干扰，保证了关节轨迹跟踪控制性能。

为实现堆垛机器人试验平台轨迹精确跟踪，采用模糊逼近估计模型信息，并将切换项模糊化的方式，提出了一种用于堆垛机器人试验平台轨迹跟踪的自适应双模糊反演滑模控制器；结合 LuGre 摩擦模型补偿前馈控制策略和自适应双模糊反演滑模控制器，进行堆垛机器人末端轨迹跟踪控制研究。结果表明：自适应双模糊反演滑模控制器控制下的末端轨迹可以很好的实现跟踪末端期望轨迹，其空间轨迹相对位置点间的均值误差为 2.47mm 以内，其中最大误差为 11.58mm，均满足试验设定的目标要求。

该论文有图 51 幅，表 10 个，引用格式 92 篇。

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图 5-4 红外镜头及红外标识点

Figure 5-4 Infrared lens and infrared identification point

NOKOV 度量动作捕捉在研究中的应用摘录

本文采用 NOKOV 动作捕捉系统来进行堆垛机器人试验平台末端轨迹测量和记录工作。其主要包括 4 个 2048\1088 分辨率的红外镜头、数个红外标识点、POE 交换机、相关标定附件(如 T 型杆和定位坐标垫)以及动作捕捉软件等，其本质上是一种被动式光学定位系统。 NOKOV 动作捕捉系统利用红外镜头不停地向试验场地中发射红外光线，当红外光线照射在红外标识点时就会发生反射，反射光从而被红外镜头上的感知元件截获，通过两个及以上红外镜头的协助，便可以唯一确定得到红外标识点在试验场地中的坐标；当获得红外标识点的一系列时间信息、坐标位置及其他相关的数据后，便可以计算分析获取其位置、方向和运动轨迹等信息。由于 NOKOV 动作捕捉系统在室内的运动测量精度较高，可以达到亚毫米级别，因而可以认为其测量出末端轨迹为真实轨迹，误差可以忽略。红外镜头及红外标识点如图 5-4 所示，红外镜头参数如表 5-2 所示。

5.2.4 末端轨迹跟踪试验系统

基于上述设备构建堆垛机器人试验平台末端轨迹跟踪试验系统，如图 5-6 所示。试验系统包括堆垛机器人试验平台本体、伺服控制器、 cSPACE 控制器、 NOKOV 动作捕捉系统及相应软件等。

引用格式 陈毅.堆垛机器人末端轨迹精确跟踪控制研究[D].中国矿业大学，2022.DOI：10.27623/d.cnki.gzkyu.2022.000487.

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堆垛机械臂设计及残余振动抑制方法研究

关键词

堆垛机械臂；实验平台；残余振动；柔性系统；振动抑制

摘要

堆垛机械臂广泛应用于生产制造领域，高速、高精度和高负重比是堆垛机械臂亟待解决的应用需求。工业堆垛机械臂伺服层级控制系统未曾考虑关节柔性和连杆柔性因素，所以无法抑制机械臂在启停阶段出现的残余振动。本文针对堆垛机械臂柔性因素所导致的残余振动问题，从堆垛机械臂设计及优化、柔性传动系统动力学建模及振动特性分析、关节运动规划和输入整形方法抑制残余振动等方面进行理论和实验研究。

工业机械臂的应用场景复杂，伺服层级控制系统被封装以保障运行的安全性，难以进行动力学算法开发调试。本文结合工业机械臂的结构特点和算法调试需求，设计搭建了堆垛机械臂实验平台，对组成结构的尺寸形状进行设计，并基于遗传算法优化臂杆尺寸；利用 Adams 仿真分析各关节极限负载工况下的力学特性，在此基础上选型动力元件，利用 Ansys 拓扑优化轻量化臂杆，提高了机械臂负重比和使用效率；采用以 DSP 为核心的控制器设计搭建了机械臂控制系统，便于 Simulink 与硬件对接。

机械臂各关节具有相对独立的传动系统，从关节空间入手，对柔性关节刚性臂杆、刚性关节柔性臂杆及柔性关节柔性臂杆三种柔性传动系统分别进行建模研究。采用 Spong 扭簧模型描述柔性关节变形，采用 Euler-Bernoulli 梁模型描述柔性连杆变形，基于拉格朗日动力学方程建立动力学模型，利用 Matlab 仿真分析柔性参数与残余振动特性之间的关系，并从传递函数角度讨论了不同类别柔性系统的结构特点，为残余振动抑制方法研究提供理论指导。

从关节空间着手，采用五次 B 样条曲线规划堆垛过程中多路径点间运动轨迹，与工业上常用的梯形速度规划方式相比，运动全程加速度与急动度光滑连续，有效抑制对柔性系统造成的振动冲击；基于输入整形技术对柔性系统输入信号进行卷积整定，通过对消柔性系统振荡极点构造典型 ZV、EI、ZVD 整形器，仿真分析了抑振效果和鲁棒性，采用随机时滞（TO）整形器优化抑振时间，分析了脉冲作用时间的选用方法。两种方法均能结合现有的关节伺服系统进行使用，具有较好的工业应用前景。

基于所设计搭建的轻型堆垛机械臂进行伺服系统参数整定及残余振动抑制实验，分别在电机力矩模式和速度模式下验证了五次 B 样条关节运动规划和输入整形抑制残余振动的有效性。实验结果表明，所提出的振动抑制方法可将残余振动幅值缩小 90% 以上。

该论文有图 74 幅，表 14 个，引用格式 118 篇。

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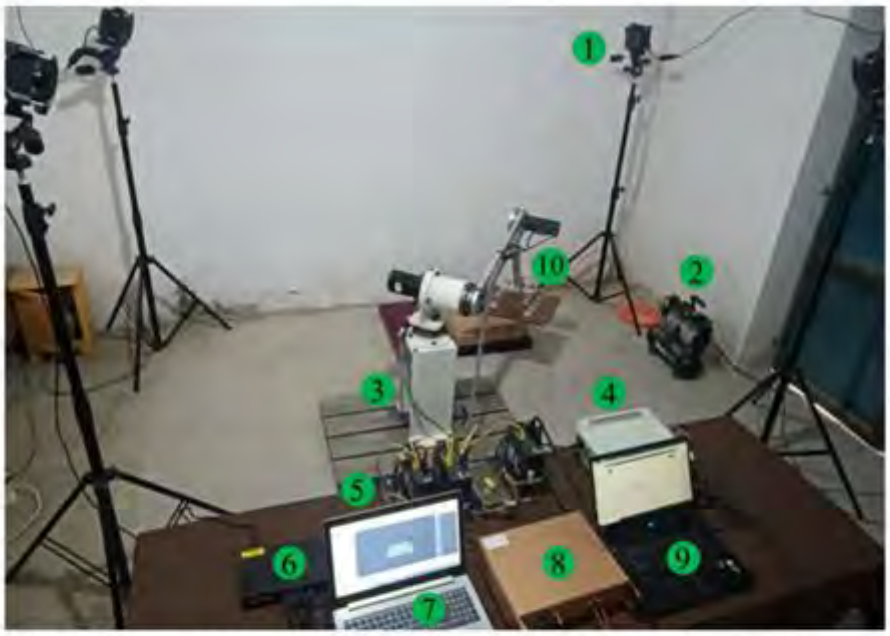

1-红外捕捉镜头；2-空压机；3-堆垛机械臂；4-信号采集系统；5-伺服驱动器；
6-动捕交换机；7-动捕上位机；8-cSPACE控制器；9-信号传输上位机；10-加速度传感器

图 5-2 实验设备整体布置

Figure 5-2 Overall layout of the experimental equipment

NOKOV 度量动作捕捉在研究中的应用摘录

为了验证第四章 Adams 点驱动方法所求得的关节转角是否正确，机械臂末端在所给关节运动规划下是否通过所给定的路径点，采用 NOKOV 红外动作捕捉系统获取机械臂末端笛卡尔空间位置。该系统使用多个 1200 万分辨率的红外镜头捕捉标识点反射的红外光，在使用标定设备对运动空间进行距离标定后，将红外标识点粘附在机械臂待测位置处，在已标定区域内任意两个镜头识别到标识点时即可获得该点空间位置坐标，辨识精度可达毫米级。但是由于捕捉系统最大采样频率较低且采样频率设置越高时对上位机性能要求越高，所以实验中仅用来获取机械臂末端空间轨迹坐标，机械臂的残余振动变化仍以加速度传感器测量。

引用格式 曹胜.堆垛机械臂设计及残余振动抑制方法研究[D].中国矿业大学，2022.DOI：10.27623/d.cnki.gzkyu.2022.000205.

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机器人与人共存中的位姿估计及避障规划

关键词

人机相对位姿；人体上肢运动预测；机器人路径规划

摘要

随着机器人技术的发展,机器人逐渐走进人类的生产生活当中,人机共融逐渐成为机器人研究领域的主要方向之一。人机安全是实现人机共融的保障。因此,如何准确估计人机相对位姿,如何进行机器人避障规划具有重要意义。对此,本文对人机相对位姿进行估计,对人体手臂运动信息进行预测,并提出一种机器人在线避障方法来保障人机的安全。主要研究内容如下:(1)对人机相对位姿估计展开研究。首先,利用光学三维动作捕捉系统获取人体手臂的位姿信息并建立其运动学模型。其次,针对障碍物遮挡导致部分标记点信息丢失的问题,基于角度传感器获取的肘关节角度来估计人体手臂末端位姿信息。再次,构建人体手臂和协作机器人的胶囊体模型,计算各胶囊体之间的最短距离,从而判断人机的相对位姿关系并实现碰撞检测。最后,在不同人机共存场景下对人机位姿估计与碰撞检测方法进行评价。实验结果表明,本方法估计的人体手臂末端位置误差在 20mm 以内,人机最短距离的最大误差为 14.53mm,能够实现人机碰撞检测。(2)对人体手臂运动的预测展开了研究。首先,提出了基于双向长短期记忆神经网络结合反向传播神经网络(Bi LSTM-BP)的人体上肢运动预测模型。接着,将双向长短期记忆神经网络结合反向传播神经网络与不同方法进行对比,对比结果表明,Bi LSTM-BP 相较于其他方法性能有一定提升。最后,通过人机跟随实验对所提算法进行验证,实验结果表明本方法可以预测人体手臂运动。(3)对人机交互下的机械臂在线避障规划算法展开了研究。首先,基于人体上肢运动预测模型获取人体上肢的运动信息。在此基础上,提出了基于改进型人工势场法的机器人在线避障规划算法。最后,通过人机共存下的机器人在线避障实验验证本文所提方法的有效性。实验结果表明,机器人与障碍物之间的最短距离始终保持 10cm 以上,机器人在运动过程中未与障碍物发生碰撞。

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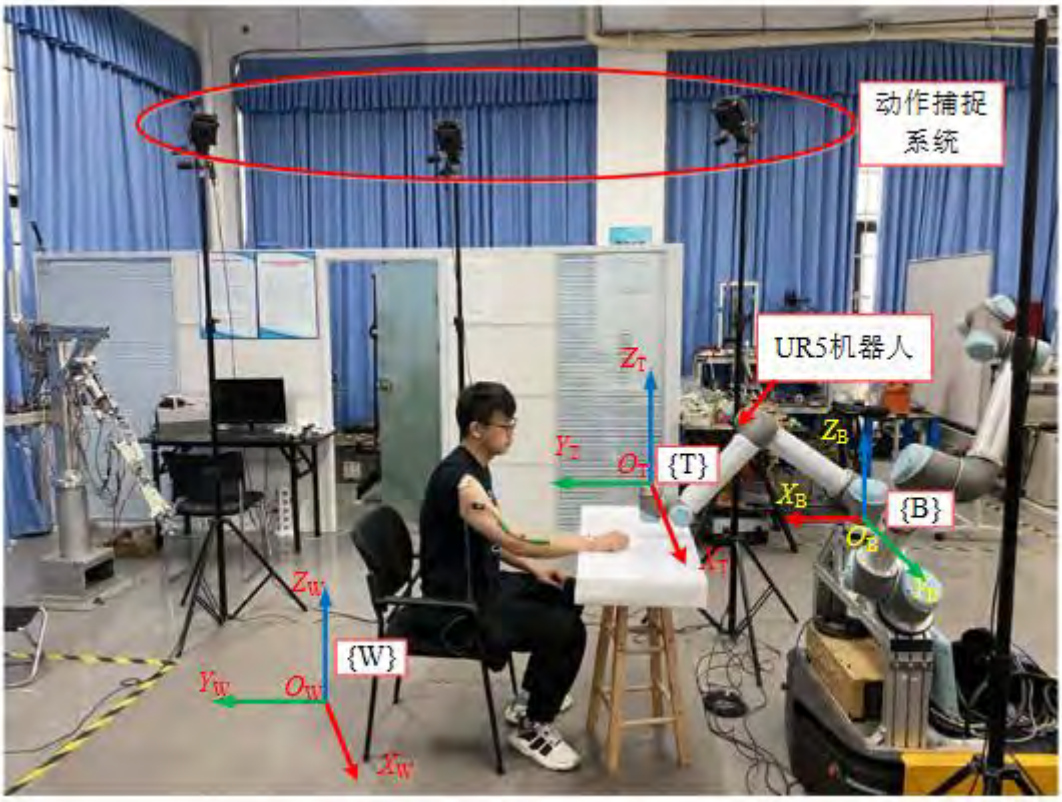

图 2-1 人机共存系统

NOKOV 度量动作捕捉在研究中的应用摘录

人机共存系统包括机器人、人和光学三维动作捕捉系统。其中，本文采用的动作捕捉系统是 NOKOV 公司光学三维动作捕捉系统。该系统采用八个型号为 Mars2H，分辨率为 2048×1088，帧率为 340Hz 的红外高速摄像机，其中，该系统定位精度为 0.02mm[70-71]。通过不同摄像机对同一个标记点的空间运动图像进行采集，标记点反射回的红外光通过信号处理、图像抓取和算法处理，从而获取每个摄像机的内参矩阵得到各镜头之间的相对位置关系，最终计算出标记点的三维空间坐标。因此，根据获取的三维坐标进行相关性分析，能够在工作空间中捕捉贴有标记点的移动物体的运动。

引用格式 汪子钦. 机器人与人共存中的位姿估计及避障规划[D]. 华南理工大学,2022.DOI:10.27151/d.cnki.ghnlu.2022.001888.

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基于递归神经网络的多移动机械臂分布式协同控制研究

关键词

全向移动机械臂；协同重复运动；分布式通信；模糊控制；递归神经网络

摘要

随着机器人智能化水平的提高，单机器人无法满足工业生产线柔性化、智能化的发展趋势，多机器人系统可以代替人工完成许多任务，如多线程操作、复杂装配、危险材料协同搬运等。多移动机械臂的协同工作中不同个体存在信息交互，传统通信方式会导致中央处理器高负载，因此需要寻求一种通信稳定、计算负担小的通信方式。在实际工业生产中，重复运动指标保证多智能体系统始末时刻位姿一致，无需额外调整时间。快速响应任务或不确定性噪声干扰导致时变逆运动学解超出设备物理限制，运动过快的全向移动机械臂导致设备的碰撞、损坏或危害工作人员安全。由于系统操作的复杂性和不确定干扰的模糊性，递归神经网络中超参数难以选择。

为解决上述问题，本文以多全向移动机械臂分布式控制与模糊自适应参数辨识为研究方向。针对重复运动指标和多全向移动机械臂分布式通信问题，设计面向重复运动的分布式二次规划方案，基于抗噪神经动力学建立分布式抗噪归零神经网络模型，控制多智能体系统完成协同重复运动，保证噪声干扰下系统集群行为的一致性。针对角度-速度约束和参数不确定性问题，设计等式-不等式约束时变二次规划，基于模糊逻辑和非凸激活函数建立分布式模糊抗噪归零神经网络模型，限制车轮和关节角度-速度在约束范围内，使用模糊系统输出值代替递归神经网络中难以确定的超参数。本文围绕分布式通信拓扑、二次规划方案、递归神经网络控制器、数值仿真和平台实验等环节展开研究。本文具体研究内容如下：

（1）针对移动平台和机械臂的协调运动规划，分析机械臂关节空间与末端执行器笛卡尔空间的映射关系，基于易于推导的移动平台逆运动学方程反解得到移动平台中心点运动状态。利用空间坐标变换集成两个子系统正运动学模型，构建全向移动机械臂整体冗余系统模型，为后续多全向移动机械臂协同控制提供运动学方程。

（2）针对分布式协同重复运动二次规划，使用分布式抗噪归零神经网络模型在线求解，控制每个个体实现协同重复运动。针对实际工程应用中不同工作场景搬运策略各异问题，提出初始构型的协同姿态控制、协同载荷运输规则和不规则物体集群控制方案。理论分析、数值仿真和平台实验验证模型稳定性和可执行任务多样性。

（3）针对多全向移动机械臂关节、移动平台麦克纳姆轮存在角度-速度边界约束和控制器参数不确定性问题，构建等式-不等式约束时变二次规划。使用分布式模糊非凸抗噪归零神经网络模型实现角度-速度联合约束和控制器参数模糊自适应调整。理论分析、数值仿真和平台实验验证模型的收敛性、求解高效性和物理可实现性。

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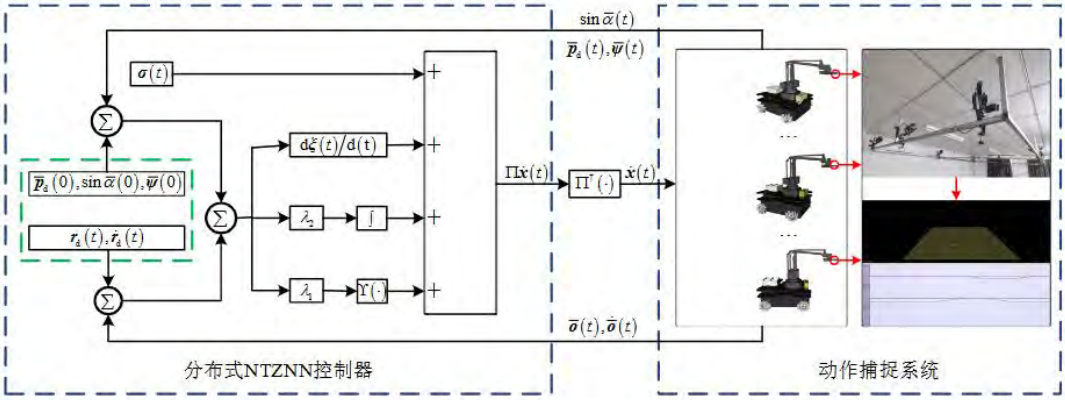

图 3.2 多全向移动机械臂协同运动控制流程图

NOKOV 度量动作捕捉在研究中的应用摘录

NOKOV 光学动作捕捉系统数据采集步骤如下：确认软件实际检测镜头数量与默认配置文件镜头数量相符，使用上下窗口 3D 视图布局；进入动捕实时播放状态，进行反光点筛选与杂点去除，保存包含镜头信息与相关参数的配置文件；加载相关配置文件，设置捕捉时间并开始录入数据；加载动捕数据进行数据截取；选中反光点并建立刚体连接，数据修复（如果有短暂数据缺失），分析图表导出数据。

引用格式 肖兴田.基于递归神经网络的多移动机械臂分布式协同控制研究[D].长春工业大学，2024.DOI：10.27805/d.cnki.gccgy.2024.000932.

链接

https://kns.cnki.net/kcms2/article/abstract?v=Uq4Diyda8XCPRF0TnCNLcPqNILeXZRUPnXY81_YNsVHCt3XtuKp3TLV5mQiX0QT2zIRYtCTO-vGzkov0E_6ktXngsFTvJVPM-M6tckL5UMq1UtyXL6OLKQ==&uniplatform=NZKPT&language=gb

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基于递归神经网络的移动机械臂轨迹跟踪和动态障碍避撞控制

关键词

移动机械臂；递归神经网络；轨迹跟踪控制；动态障碍；避撞控制

摘要

随着自动化产业发展，为提高生产效率和质量，降低人力成本与生产周期，企业对自动化生产设备需求不断增加。移动机械臂作为一种灵活高效自动化装备，可满足多种生产环境需求，其控制技术备受关注。然而，由于移动机械臂应用场景复杂多样，传统控制方法逐渐展现不足之处。工程环境常存在噪声干扰，降低移动机械臂轨迹跟踪精度。此外，移动机械臂关节具有活动范围约束，超出物理限制将导致机械臂受损，无法执行轨迹跟踪任务。在复杂运行场景中，移动设备与工作人员可能阻挡移动机械臂行走路线，若移动机械臂缺乏避撞能力将发生碰撞情况，引发安全事故。

为解决上述问题，本文以移动机械臂轨迹跟踪控制与动态障碍避撞控制为研究方向。针对关节约束问题与噪声干扰问题，基于抗噪神经动力学提出一种轨迹跟踪控制模型，使噪声影响下轨迹跟踪误差收敛至零，限制各关节于关节约束中，提高移动机械臂精确性、可靠性。针对动态障碍避让问题，基于递归神经网络设计一种避撞控制模型，使移动机械臂避让未知动态障碍，无碰撞完成轨迹跟踪任务，增强移动机械臂灵活性、安全性。针对移动机械臂控制研究中关键科学问题，本文围绕问题构建、控制器设计、理论分析、仿真与平台实验等环节展开研究，具体研究内容如下：

（1）针对移动机械臂运动学建模，剖析移动机械臂运动特性，利用 D-H 法建立机械臂运动学方程，通过麦克纳姆轮速度分解构建全向移动平台运动学模型。结合坐标旋转矩阵，整合机械臂与全向移动平台运动学方程，构建基于世界坐标系的移动机械臂整体运动学模型，为建立轨迹跟踪控制模型与避撞控制模型奠定基础。

（2）针对关节约束与噪声干扰下轨迹跟踪控制方法，考虑物理关节限制构建轨迹跟踪问题，利用松弛变量将时变不等式约束问题转化为时变等式问题，建立一种抗噪轨迹跟踪控制模型。通过理论分析验证轨迹跟踪控制模型在不同噪声干扰下具有收敛性。进行仿真实验验证轨迹跟踪控制模型有效性、高效性和优越性。此外，通过平台实验验证轨迹跟踪控制模型可实现性，表明模型在工程中具有应用价值。

（3）针对移动机械臂轨迹跟踪时避撞控制设计，剖析动态障碍避让问题，耦合轨迹跟踪控制，提出一种避撞控制模型以解决动态障碍阻挡、关节约束及噪声干扰问题。理论分析表明避撞控制模型具有收敛性、鲁棒性。仿真对比实验验证避撞控制模型有效性和优越性。平台实验证明避撞控制模型可实现性，提升移动机械臂复杂环境下适应性、安全性。

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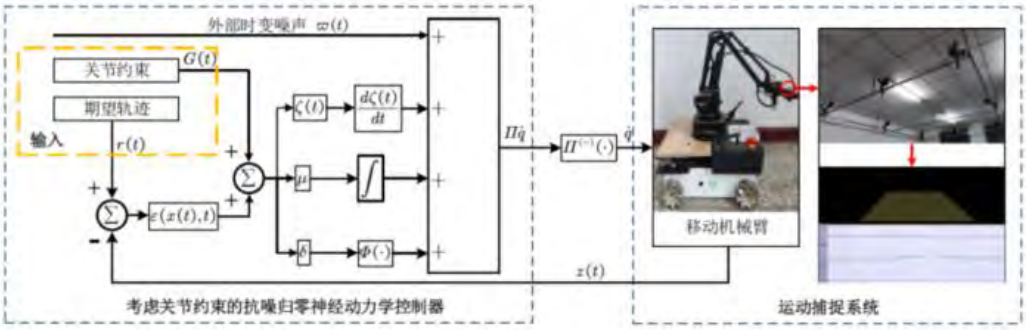

图 3.14 NSZNN-JAC 模型（3-15）平台实验验证框图

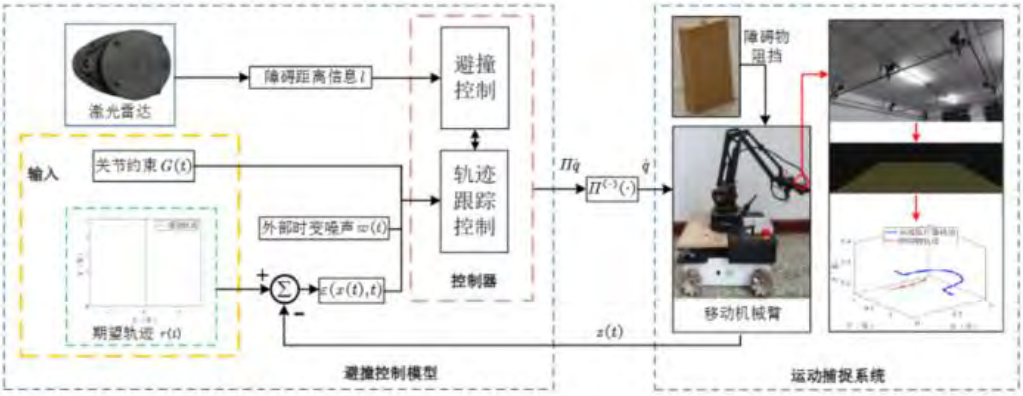

图 4.6 避撞控制模型（4-10）平台实验验证框图

NOKOV 度量动作捕捉在研究中的应用摘录

由于需要测量工具以精确获取移动机械臂实际轨迹，本文中采用光学三维动作捕捉系统 NOKOV 作为测量工具。图 3.14 中红色圆圈内反光点放置于移动机械臂末端执行器上，可被 NOKOV 识别捕捉。

引用格式 费宇哲. 基于递归神经网络的移动机械臂轨迹跟踪和动态障碍避撞控制[D].长春工业大学，2024.DOI：10.27805/d.cnki.gccgy.2024.000398.

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基于递归神经网络的移动机械臂轨迹跟踪控制方法研究

关键词

移动机械臂；递归神经网络；轨迹跟踪；路径规划；时变非线性方程组；

摘要

由于移动机械臂操作空间的扩大,移动平台与环境交互能力的提高,它在交通运输、搜救、安全和监控等领域得到广泛应用。在运输过程中为节约运输成本,移动平台执行复杂任务需要进行路径规划,即选取起始点到目标点过程中的最优节点。然而在实际工况下普遍存在干扰移动机械臂运动的外力、环境冲击力、电磁干扰以及信号传输过程中的各种噪声,这些扰动会对模型求解精度、稳定性与任务完成产生重大影响,导致轨迹跟踪任务失败,并且移动机械臂存在难以实现协同控制和抗外部扰动能力差等缺点。因此需要设计一种抗噪型递归神经网络算法解决带有扰动的移动机械臂轨迹跟踪控制问题。

针对上述问题本文进行深入研究,其主要研究内容如下:

（1）针对移动机械臂的跟踪控制问题,建立移动平台的运动学方程与机械臂的运动学方程,利用空间坐标变换矩阵得到基于世界坐标下的移动机械臂整体运动学方程,为后续解决移动平台与机械臂的协同控制奠定基础。

（2）针对移动机械臂的轨迹跟踪问题,将轨迹跟踪问题转换为时变非线性方程组求解问题。在传统归零神经网络（Zeroing Neural Network,ZNN）与梯度神经网络（Gradient Neural Network,GNN）基础上设计一个抗噪型归零神经网络（NoiseTolerant Zeroing Neural Network,NTZNN）消除外部噪声扰动,理论证明 NTZNN 模型能消除外部噪声的扰动。数值仿真结果表明 NTZNN 模型能收敛于带有外部干扰的非线性方程组的精确解。

（3）针对路径规划问题,构造一个与能量函数相关的离散型非线性函数,使得最低能量状态的解对应最优路径下的状态解,将连续型 ZNN 离散得到离散型 ZNN 求解非线性优化问题,仿真实验表明离散型 ZNN 迭代求出最低能量函数,此时对应最优状态的解,进而确定移动平台的运动路径。

（4）针对轨迹跟踪问题,设计了一种 NTZNN 控制器驱动末端执行器完成跟踪任务。仿真实验表明 NTZNN 算法对比 GNN 算法、ZNN 算法具有良好的去噪能力。最终通过实物平台验证 NTZNN 模型具有良好的优越性、抗噪性。

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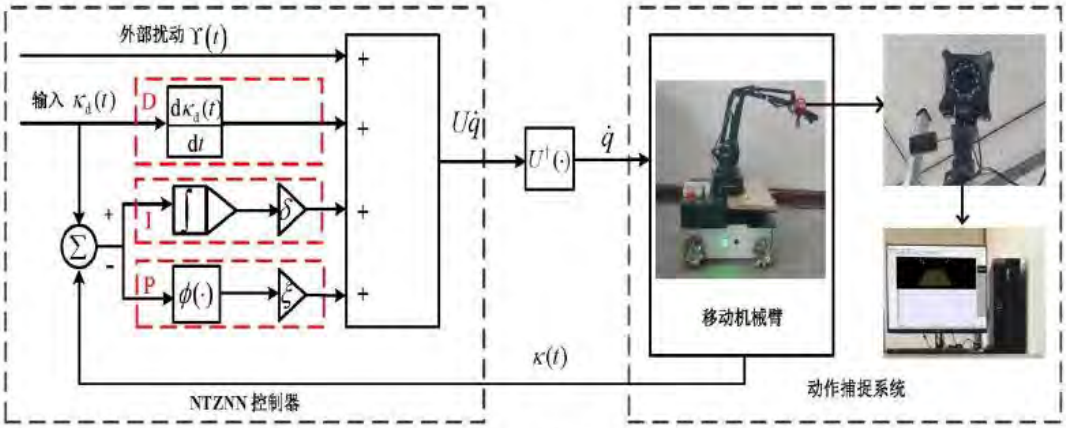

图 5.12 算法验证原理图

NOKOV 度量动作捕捉在研究中的应用摘录

作为 ROS 移动机械臂操作系统的"寄生环境"Ubuntu 系统，它安装 Eigen 库降低 C++程序代码的复杂性，同时提高系统的实时性，此外利用 NOKOV 生产的光学动作捕捉系统采集 ROS 移动机械臂在空间下的运动数据。基于 Windows 系统安装"seeker Driver1.6.2.x"与"Seeker1.6.2.1"文件。在 Seeker 软件建立数据存档配置文件并加载配置文件。将工作站与镜头连接，更改工作站页面布局，使得整个页面上方是连接镜头区域，页面下半部分为采集数据区域。将移动机械臂末端执行器位置贴上 Marker 点（如图 5.12）放入动作捕捉场地中央位置如图 5.11，点击工作界面镜头切换 2D 画面能捕捉到空间下的杂点、反光点，处理除移动机械臂上 Marker 点以外的杂点，保证数据采集环境无干扰。上述为移动机械臂末端执行器的位姿数据采集奠定基础。

引用格式 周彦鹏.基于递归神经网络的移动机械臂轨迹跟踪控制方法研究[D].长春工业大学，2022.DOI：10.27805/d.cnki.gccgy.2022.000073.

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基于递归神经网络的移动机械臂运动规划与避撞控制方法研究

关键词

移动机械臂；递归神经网络；重复运动；轨迹跟踪

摘要

由于移动机械臂灵活度高、操作空间大,它在焊接、喷漆以及装配实际工程领域得到广泛应用。移动机械臂在实际装配时,为了减小能量消耗和提高生产效率,需要移动机械臂的位姿和末端位置尽可能与初始构型相吻合,即移动机械臂完成重复运动任务。此外,在执行复杂任务时,移动机械臂将会遇到障碍物,需要其完成轨迹跟踪和协同控制且避免与障碍物发生碰撞。而且,在实际工况下普遍存在干扰移动机械臂运动的电磁干扰、模型干扰以及信号传输过程中的各种噪声,这些扰动会对模型求解精度、稳定性与任务完成产生影响,导致移动机械臂重复运动和避撞任务的失败。因此,有必要设计一种非凸抗噪型递归神经网络算法解决带有扰动的移动机械臂重复运动、轨迹跟踪和避障控制问题。针对上述问题本文进行深入研究,其主要研究内容如下:(1)针对移动机械臂的运动规划问题,利用 D-H 方法和空间坐标变换矩阵得到基于世界坐标下的移动机械臂运动学方程,为后续解决移动机械臂的运动规划奠定基础。(2)通过二次型性能指标、移动机械臂的物理约束和整体运动学方程将移动机械臂非凸速度约束、轨迹跟踪和正交重复运动转化为时变二次规划问题。利用递归神经网络求解时变二次规划问题,控制移动机械臂完成重复运动任务。正交重复运动时变二次规划方法能够消除位置误差,提高控制精度。数值仿真表明递归神经网络模型能够控制移动机械精确完成重复运动任务。(3)通过二次型性能指标、移动机械臂的速度约束和整体运动学方程将移动机械臂重复运动、速度约束、轨迹跟踪转化为时变二次规划问题。利用非凸抗噪归零神经网络求解时变二次规划问题,控制移动机械臂在有外界干扰下完成重复运动、速度约束、轨迹跟踪任务。理论证明非凸抗噪型归零神经网络模型能抑制外部噪声扰动。数值仿真和平台实验验证非凸抗噪型归零神经网络模型能够消除外界噪声干扰,使移动机械完成轨迹跟踪、速度约束和重复运动任务。(4)通过二次型性能指标、物理约束和移动机械臂运动学方程将重复运动、轨迹跟踪、物理约束和避撞转化为时变二次规划问题。利用原始对偶神经网络求解时变二次规划问题,控制移动机械臂完成避撞、轨迹跟踪、关节约束和关节速度约束。数值仿真结果和平台实验验证原始对偶神经网络模型能控制移动机械臂完成轨迹跟踪、重复运动、关节约束、关节速度约束和避障任务。

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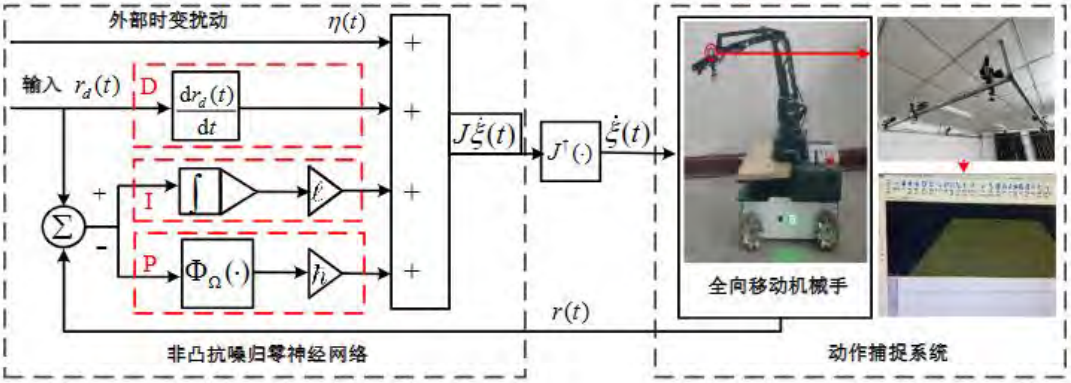

图 4.9 移动机械臂的算法验证结构框图。

NOKOV 度量动作捕捉在研究中的应用摘录

作为 ROS 移动机械臂的操作系统的"寄生环境"Ubuntu 系统，在移动机械臂进行平台上实验调试。利用 NOKOV 产生的光学运动捕捉系统实时捕捉移动机械臂末端执行器空间标记的位置信息，即图 4.9 中红色圈出的点。利用 Matlab 软件绘制光学动作捕捉系统采集到的具体数据，并通过与期望路径的比较验证了 NCNSZNN 模型的有效性。

引用格式 唐世军. 基于递归神经网络的移动机械臂运动规划与避撞控制方法研究[D].长春工业大学,2023.DOI:10.27805/d.cnki.gccgy.2023.000666.

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基于点云与位姿信息的机械臂辅助超声扫描系统研究

关键词

机械臂辅助；路径规划；动作捕捉；超声诊断；点云

摘要

在医疗领域,超声成像凭借其无创、非侵入性、诊断方便等优点,得到了广泛的应用。但在医疗落后地区(如小岛、渔村、贫困山区、偏远军事基地),由于缺少专业的超声影像医生,病人不能得到专业、及时的救治,进而错失黄金诊断时间。此外,长期单调且重复的动作使得超声影像医生患肩周炎、眼疾等职业疾病的风险大大增加,很大程度上影响了医生的正常工作和生活。基于上述问题,研究出一种新的超声扫描方式已经成为当下亟需解决的难题。近年来,机械臂辅助超声扫描技术因其简洁性与高效性逐渐进入人们的视野,在腹部、消融以及骶骨扫描等方面都进行了广泛地探索应用。应用过程中,暴露出许多问题和不足,如辅助扫描部位受限、时延大、位置精度低等。针对目前此研究方向中普遍存在的问题,本文通过结合机械臂、视觉及姿态信息,实现了一种远程机械臂辅助超声诊疗系统,旨在为临床进行远程超声扫描与诊断提供智能化平台。本文的主要贡献如下:(1)设计实现了一种基于点云的期望扫描区域定位方法。本方法主要解决已有研究中机械臂只能简单地沿着探查部位中线或特定直线进行扫描这一缺陷,通过提取超声医师在点云下选取的期望点的位姿信息,然后进行坐标变换,最后通过工作空间规划来控制机械臂运动到期望点。实验结果表明,基于点云的路径规划方法的响应时间与路径执行时间分别为 0.6572s 与 0.9577s,三轴的位置误差均值约为 2.1mm。相比之下,本系统的响应时间、位置误差等都优于其他方法,具备更好的应用性。(2)设计并实现一种基于位姿信息的机械臂实时跟随方法。本方法解决了已有机械臂辅助超声扫描方法探查部位受限等问题,通过位姿传感器实时捕捉医生的操作动作,采用机器人逆运动学算法实现机械臂的远程精准实时跟随。经过仿真实验与真实临床测试,本方法在机械臂端的位置跟随轨迹与虚拟探头的位置轨迹一致,且机械臂可完全复现出虚拟探头的运动姿态,X 轴、Y 轴以及 Z 轴的位置误差均值约为 0.74mm、0.88mm 和 0.80mm,所需时延与跟随精度均优于已有研究,具备很好的普适性与应用前景。(3)设计并实现一个远程机械臂辅助超声诊疗系统。系统中通过查询机械臂端、专家端以及超声探头端的实时流地址,将三者的实时信息上传到系统中显示,方便医生实时观察远程机械臂的操作情况。同时可以实现多方专家在线对患者的超声影像进行分析与诊断,并可借助系统的智能诊断模块对机械臂实时采集的超声影像进行识别与处理,有助于推动临床智能医学的发展。

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图 4-1 实验环境示意图

NOKOV 度量动作捕捉在研究中的应用摘录

基于位姿信息的全自动机械臂跟随方法由动作捕捉设备、专家端 PC、机械臂端 PC、10 孔交换机、虚拟仿真探头、机械臂、超声探头以及硅胶仿体实现，实验环境如图 4-1 所示。首先专家端的超声医师手持带有 marker 反光球的虚拟仿真探头在动作捕捉设备的视野范国内进行移动，系统实时捕提医生在每一时刻的位置和姿态信息，经交换机发送给机械臂端的 PC 进行数据的滤波、坐标转换等工作，驱动机械臂夹持超声探头在人体硅胶模型上进行位姿的复现，实验所使用的设备以及开发环境如表 4-1 所示。

引用格式 张德彩. 基于点云与位姿信息的机械臂辅助超声扫描系统研究[D].山东大学，2022.DOI：10.27272/d.cnki.gshdu.2022.001702.

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基于光学定位的机器人轨迹演示示教系统研究

关键词

机器人演示编程；光学定位；人机交互；机械臂避障

摘要

工业机器人以其效率高、稳定可靠、重复精度好等优势得到了广泛应用。现代制造业的发展对机器人的智能性和灵活性提出了更高要求。在焊接、涂胶、切割、3C、光伏和新能源领域,有许多应用的需求是以小批量、多品种、短周期为特点,在机器人使用过程中传统的示教编程难以高效且准确的生成机械臂运动指令,而无示教器编程的演示示教技术应运而生。演示示教不仅可以灵活快速生成机械臂作业轨迹,并且不需操作者逐点示教,从而大大加快机械臂在作业环境中的示教编程效率。本论文将开展工业机器人的轨迹演示示教系统研究。首先,综合分析各种空间定位技术的优势与不足,确定基于红外激光定位和光学动捕两套技术方案作为机器人作业路径的采集模块。基于红外激光定位原理给出路径点的坐标计算方法和定位误差分析。基于笔形示教器设计机器人标定方法,选定 60-90 Hz 的频率在 1 mm 误差以内采集操作者的演示路径。其次,根据机器人平稳运行且速度均匀可控的要求,开发位姿轨迹规划生成模块。从滤波后的位置轨迹中提取特征点拟合非均匀有理 B 样条(NURBS)曲线,进行速度规划和等时插值。基于演示过程中系统记录的姿态点拟合四元数样条曲线,生成与位置样条相对应的等时插值点,通过机械臂逆解求解器得到位置和姿态样条曲线对应的各个关节运动控制指令。再次,为了提高本系统对复杂作业环境的适应性,开发面向一定约束环境下的演示示教编程。在有限约束的自由空间,基于深度视觉三维重构建立机械臂作业环境的碰撞检测模型。提出了一种人工势场(APF)-快速扩展随机树(RRT)融合算法,使得系统能够在关节空间内搜索返回一条能量最优的无碰撞路径,以实现受约束环境下的机械臂轨迹演示编程。最后,进行系统搭建和实验验证,对应用在本系统的两种光学定位方案使用 UR5 机器人测试其位姿跟踪性能,并进一步搭建了演示编程示教的验证平台,设计了面向平面规则路径和空间复杂零件的轨迹演示编程示教实验并与拖动示教作对比,从示教效率和复现精度两方面对本系统进行性能评估。

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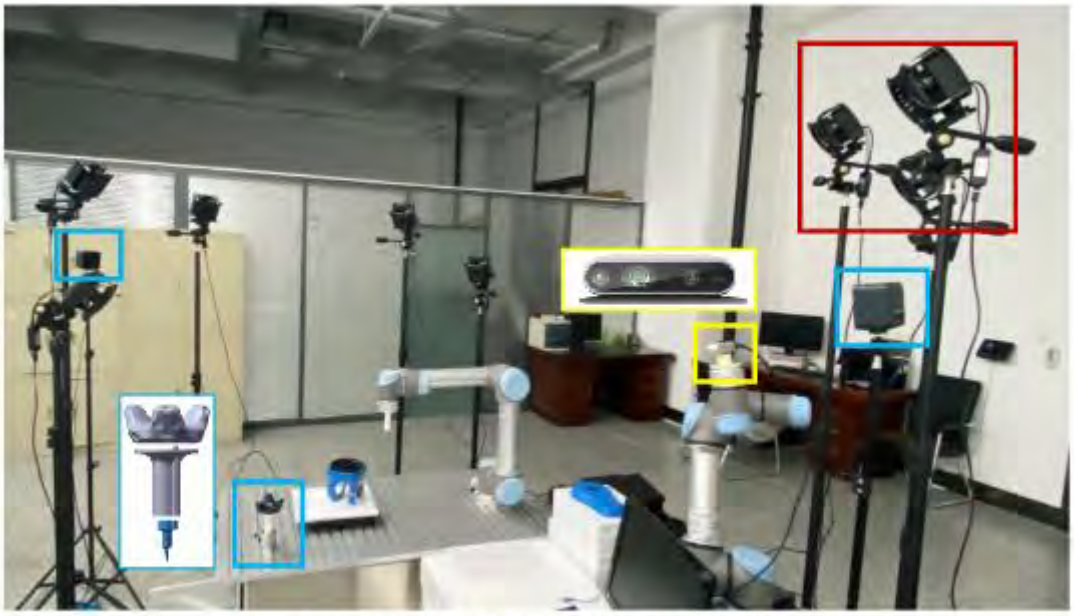

图 5- 8 结合动作捕捉系统的平台搭建

NOKOV 度量动作捕捉在研究中的应用摘录

本课题使用 NOKOV Mars2H 型号动作捕捉系统，跟踪的示教笔如图 2-12 所示，在末端固定五个反光靶球，建立如图 2-12 所示跟踪坐标系。整体而言，Nokov 动作捕捉系统具有比 HTC 定位系统更高的位姿定位精度。虽然两者都满足本课题提出的 1mm 左右轨迹示教精度的要求。

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基于先验的复杂场景三维重建

关键词

自主三维重建;数字孪生;多智能体策略;三维高斯泼溅;铰链物体;

摘要

当人们在虚拟的城市街景中游览,当自动驾驶汽车在几何构建的镜像世界穿行,当机器人在数字化的孪生空间中学习任务策略,三维重建技术正在重构人类感知现实的范式。传统的三维重建方法与策略的任务目标以重建简单场景为主,即重建小规模局部区域的外表面。然而,日常生活中还存在一类更加复杂的场景,即具有一定空间维度、结构和运动模式的场景。对于这一类场景,如何使用针对性的方法将其表面纹理这一外在属性,以及物体语义、机械结构等内在属性进行准确、高效且智能的重建,仍然是需要进一步深入研究且颇具挑战的课题。本文观察到,对于这一类复杂场景重建问题,存在许多可以借助的先验知识用来构建更加高效、高质量、鲁棒的重建策略。 首先,对于大规模未知室内场景而言,其具有场景大且未知的复杂性。为了方便下游任务的需要,应构建场景中物体的语义信息,以及针对具有丰富细节的物体进行准确的重建,同时又要考虑重建的效率问题。针对于此,本文利用任务的先验性,事先将任务拆分成了探索与重建两种类型,并提出了两种任务的生成方法与对应的扫描模式,同时采用了多机器人自主扫描的形式,机器人可以根据当前场景与自身状态动态地切换模式。之后,本文将任务的分配问题建模成多起点的多旅行商问题(Multi-Depot-Multi-Traveling-Salesman-Problem)并通过一个有效的启发式方法解决。最后,本文针对中心化系统存在的分配任务不平均时机器人等待问题提出了异步协同的执行策略,进一步地提高了执行效率。经过大量实验,并对比各项结果,本文所构建的中心化异步多机器人自主重建系统,能够在一次作业中,以高效率完成对未知室内场景的重建任务,同时实现精准的语义理解,同时达到较高的重建质量。 对于三维重建而言,仅仅构建场景以及物体的表面纹理并不足够,许多生活中常见的物体还带有旋转或者平移的可移动部件,如抽屉、柜子等。因此,构建铰链物体(Articulated Object)的数字孪生也是三维重建的重要任务之一。不同于表面重建工作,重建铰链物体具有复杂的优化目标。不仅需要构建物体的外观与几何,还需要学习铰链物体的铰链逻辑以及可移动部件的语义分割,对于这三类高耦合度的参数来说,同时进行优化是一件非常困难的事情。本文紧接着利用三维高斯泼溅(3D Gaussian Splatting,3D-GS)方法,通过使用物体的移动部件在两个状态下的多视角图像,借助铰链物体运动结构(旋转或平移)的先验,解决了这一挑战,以构建铰链物体的数字孪生。本文通过一个自监督的方法,能够自主地在部件级别上学习建模形状和外观,并同步优化运动参数,重建过程不依赖于任何先验知识。本文的方法通过多步优化过程解耦了多个高度相互依赖的参数,从而实现了一个稳定的优化过程和高质量的重建结果。大量的实验结果表明,在可比较的方法中,本文的方法在部件分割精度、运动估计精度和视觉质量方面都得到了高质量的结果。 区别于生活中的铰链物体,机械臂具有更加复杂的机械结构,不仅有机械臂主体部

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分串联的连杆结构,也有夹爪上关节的并联结构,使用以往的对铰链物体的重建方式难以进行构建。已有的方法往往需要人工手动对机械臂的部件进行分割,并且利用人工的方法将重建的场景与模拟器中的场景的坐标系进行对齐以进行下游任务,人工参与使得重建的过程十分耗时费力,缺乏智能性。本文利用机械臂自带 URDF 文件中的 CAD 模型作为先验,使用三维高斯泼溅作为表达,构建出了具有高真实感的可受控制信号操控的机械臂及其场景的数字孪生。基于此重建结果,本文尝试解决了具身智能中的将以 RGB 视觉为输入的机械臂任务策略从模拟器到真实机器人迁移的任务。一系列的实验表明,本文方法可以将机械臂的重建结果与真实场景进行精准匹配,且基于重建的机械臂及场景的训练策略能有效地对虚拟到现实的策略迁移问题进行解决。 本文的研究为多种复杂场景下的三维重建提供了重要的技术支持。通过多机器人自主扫描系统,本文实现了对未知室内场景的高效重建与语义理解,解决了多机器人在探索与精细化扫描之间的平衡问题。此外,本文提出的铰链物体重建框架在部件分割、运动估计和视觉质量方面均取得了显著成果,为铰链物体的数字孪生构建提供了新的解决方案。这些研究成果不仅推动了具身智能在室内场景中的应用,也为未来智能机器人在复杂环境中的自主操作与交互奠定了坚实的基础。同时,针对更加复杂的机械臂的铰链结构,本文提出了基于三维高斯泼溅的创新方法,有效对真实生活中的机械臂进行了重建,进而在一些操控任务中弥合了虚实鸿沟,提升了任务执行过程中的成功率。为充分验证本文方法的性能,本文开展了一系列全面且深入的研究。本文与各类开源基准方法进行了详尽对比。综合实验数据及对比分析结果,有力地证实了本文所提出方法的有效性与可行性。

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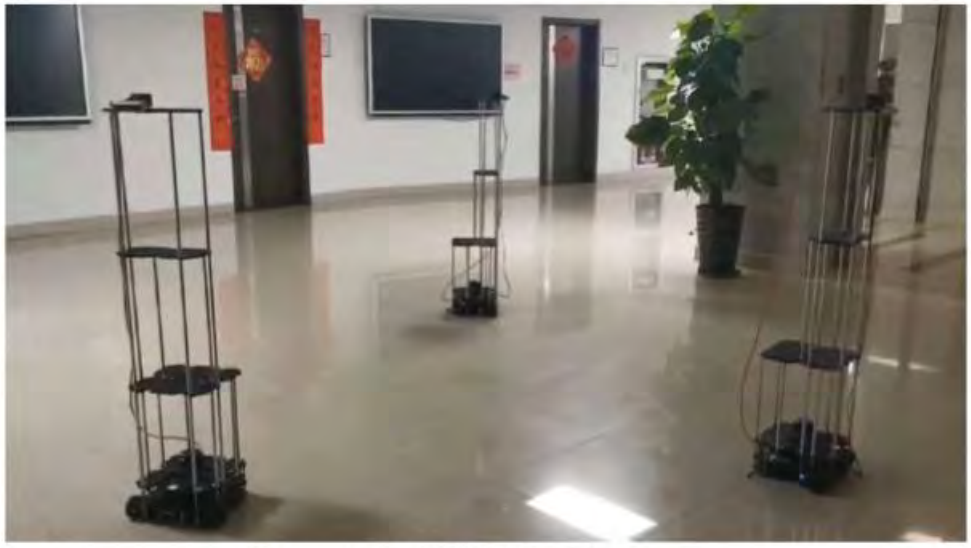

图 3.6　本章方法所使用的定制机器人平台。

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（3）实验平台
本章的系统运行在机器人操作系统(ROS)之上，它支持机器人的标准行为，如导航和手臂动作。为了便于开发和评估，本章使用 Gazebo\[181 框架作为本章的模拟器，它可以模拟与现实世界的交互。本章进一步向深度图中添加合成噪声以模拟现实中的相机噪声，就像\[1821 的工作那样。在模拟器中，本章使用 Fetch 机器人。每个机器人配备一个安装在顶部的 PrimeSense Carmine 1.09、一个手持的 RealSense 深度相机 D435i，以及一个 SICK2D 传感器。SICK 传感器用于机器人跟踪，这对于探索任务和地图合并是必要的。一台台式 PC 处理所有数据，其配置为英特尔(R)酷睿(TM)i7-10700KCPU(3.8GHzx8)、64GB 内存和英伟达 GeForce RTX3080GPU。GPU 用于形状补全(GR-Net)和实例分割(MaskR-CNN)，总共大约需要 16GB 内存和 10GBGPU 内存。本章的方法利用了所有机器人捕获的 RGB-D 数据和相机位置。
对于实际实验，由于价格较低，本章使用 Turtlebot3，如图 3.6 所示。每个机器人配备一个 RealSense 深度相机 D435i，以及一个 RPLIDAR A2M8 360°激光雷达扫描仪。场景中通过 Nokov 运动捕捉相机(https\://www\.nokov.com/) 辅助定位。当机器人移动超出 Nokov 的捕捉范围时，激光雷达扫描仪也可以跟踪机器人的位置。

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基于阻抗模型的双机器人对等协作控制研究

关键词

双机器人协作；轨迹规划；SimMechanics；阻抗控制；对等架构

摘要

在弧焊焊接领域，传统的由焊接机器人+变位机+工装夹具组成的焊接工作站已不能满足当前小批量、定制化的柔性自动化生产需求。多机器人协作焊接系统具有更强的作业能力、更大范围的工作空间、更灵活的系统结构和组织方式，可以克服传统焊接工作站的缺点，是焊接自动化的发展方向，具有广阔的市场应用前景。

多机器人协作焊接系统包含工件搬运机器人和焊接机器人，其在带来诸多优势的同时，也带来了更为复杂的控制问题。对于一个具有两台工件搬运机器人和一台焊接机器人的多机器人焊接系统，如何控制两台工件搬运机器人的协作运动是多机器人焊接成败的关键。其主要难点和关键问题有：①双机器人协作的运动轨迹规划；②双机器人协作系统的建模；③双机器人协作的位置/力协调控制。因此，研究并解决上述双机器人协作系统中的关键问题并总结出其中的理论方法是实现多机器人协作焊接的基础，对于发展多机器人协作控制的理论与实践均具有重要的意义。为解决上述问题，本文的研究思路是：针对双机器人协作运动的轨迹规划问题，本文重点研究双机器人协作夹持钢管拼接形成的马鞍形曲线焊缝，采用面向对象的轨迹规划方法；针对双机器人协作系统的建模问题，本文采用对等架构模型以提高系统的响应速度；针对双机器人的位置/力协调控制问题，本文采用基于位置的阻抗控制方法对双机器人间的位置/力进行调节。目标是实现双机器人协作夹持钢管运动，使马鞍形曲线焊缝满足船形焊位姿；并且在协作运动过程中，控制工件与工件之间的接触力/力矩在合理的范围内。

首先，论文对双机器人协作夹持钢管拼接形成的马鞍形曲线焊缝的轨迹规划进行研究，采用面向对象的轨迹规划方法，并基于 MATLAB/SimMechanics 搭建了仿真平台，对提出的轨迹规划方法进行验证。其次，论文采用对等架构对双机器人夹持钢管这一研究对象进行数学建模，确立了被夹持工件与两个机器人末端之间力、位置、速度等的映射关系，并建立了双机器人协作系统的控制框图。然后，论文采用基于位置的阻抗控制方法调节双机器人协作过程中的位置/力关系，并详细分析了阻抗控制的原理及其实现方法。紧接着，论文详细介绍了双机器人协作系统的设计思路，基于实验室开发的开放式总线控制器，针对研究目标实现了高效稳定的双机器人协作控制系统。针对研究目标实现了高效稳定的双机器人协作控制系统。

最后，论文以两台埃斯顿 ER16 通用六关节机器人为控制对象，完成了双机器人协作夹持钢管拼接运动。实验结果表明双机器人在完成规划轨迹运动的同时，通过阻抗控制的调节作用，工件与工件之间的接触力/力矩被控制在合理的范围内，从而验证了本文所设计的双机器人协作系统的实时性、高效性和可靠性。论文的研究成果为实现三机器。

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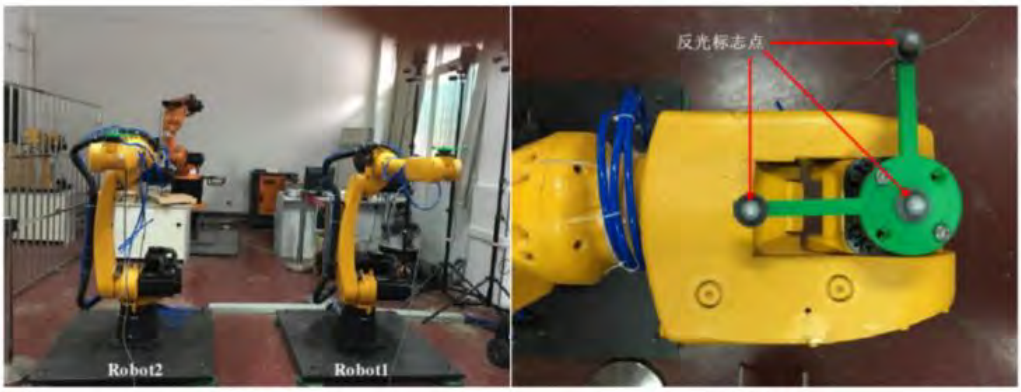

(a) 机器人　　(b) 反光标志点

图 6-8 待标定机器人

(a) 摄像头　　(b) 设备布置情况

图 6-9 标定设备布置

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双机器人基坐标系的标定
为了实现对双机器人协作系统运动轨迹的规划，首先需要确定双机器人基坐标系的相对位姿。本课题使用北京度量科技有限公司研发的 Nokov 光学三维动作捕捉系统来测量两个机器人基坐标系的相对位姿。

引用格式 陈明.基于阻抗模型的双机器人对等协作控制研究[D].东南大学,2018.

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面向飞行机械臂的实时目标检测与定位算法

关键词

飞行机械臂；YOLOv5；RGB-D；目标检测；模型量化；位姿估计；

摘要

飞行机械臂要完成自主抓取的任务，对目标物的识别与定位尤为关键。当前飞行机械臂视觉识别算法多采用传统的特征提取等方法。为提升目标物识别及定位的精度和效率，本文设计了一种基于 YOLOv5 深度学习目标检测算法和 RGB-D 传感器的视觉识别与定位算法，该算法可以实时检测目标物并对其位姿进行估计，为飞行机械臂的抓取工作服务。同时针对深度学习算法计算量庞大，在嵌入式端无法实现高性能实时检测的问题，引入了模型量化技术优化算法，大幅提升算法推理速度。本文介绍了算法的整体框架及实现过程，利用 COCO 数据集和动作捕捉系统分别验证了目标检测和位姿估计部分算法的有效性。

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图 3　目标物位姿估计实验平台

Fig.3　Object pose estimation experimental platform

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本文根据飞行机械臂工作特点，设计了一种基于 YOLOv5 目标检测算法 RGB-D 传感器的实时目标检测与定位算法，在 NVIDIAXavierNX 嵌入式开发板上构建了整体的视觉系统。该算法通过对彩色图像的识别得到目标物边界框 ，并根据传感器得到的深度图像来提取目标物区域的点云 。算法利用模型量化方法优化深度学习推理过程 ，在识别精度基本不变的情况下大幅提升了算法处理速度。本文选用 COCO 数据集对算法目标检测部分进行测试 ，该数据集是目标检测领域广泛使用的开源数据集，可以较好地检验目标检测算法模型的综合性能。优化后的算法在 COCO 数据集的测试显示在处理时间降低到 33 ms 的同时平均精确率均 值（Meanaverageprecision，mAP）的下降仅在 0 .001 以内。算法通过 RGB-D 传感器结合点云滤波及改进 ICP 算法对目标物位姿进行估计，最终利用 NOKOV 动作捕捉系统（Motion capture，MO-CAP）验证了该算法的有效性。算法可以为飞行机械臂的抓取工作提供实时且精确的目标物位置和姿态信息，帮助完成复杂和危险环境下对目标物 的自主飞行和抓取。

引用格式 张睿,王尧尧,段雅琦等.面向飞行机械臂的实时目标检测与定位算法[J].南京航空航天大学学报,2022,54(01):27-33.DOI:10.16356/j.1005-2615.2022.01.003.

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面向批量定制的装配建筑数字建造技术体系——以装配式木构建筑创新为例

关键词

批量定制；装配式建筑；建筑机器人；数字建造；木构建筑

摘要

面对高质量城市建设和乡村振兴需求，建筑的智能建造与工业化日益成为装配式建筑产业升级的重要抓手。建筑机器人智能建造装备的批量定制生产能力能够有效应对装配式建筑大批量、柔性的生产需求。定制开发的机器人工具端为灵活高效的建造工艺体系奠定了基础；机器人智能感知与反馈技术提高了生产系统对多样化的复杂建造任务的适应能力；基于计算设计平台的机器人控制软件直接将几何逻辑转译为建造逻辑，推动装配式建筑设计与建造一体化发展。文章以木构建筑的机器人装配式建造为例，诠释面向批量定制的装配式建筑数字建造技术体系的内涵。

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> *4.1.3　感知系统*
> *智能感知系统在机器人建造中的应用使机器人建造平台能够对材料、工具、建造过程进行实时监测，提高机器人系统对复杂建造场景的适应能力。同济大学机器人预制建造平台配备了红外动作捕捉系统作为核心传感器，系统包括 12 台红外相机，均匀分布在机器人工作空间的四周。相机以 200 H z 的频率记录空间中标记小球的位置信息，　并将信息汇集到交换机（图 5）。在计算机端，运动分析软件 NokovSeeker 可以从交换机获取数据并执行数据处理、系统标定、刚体定义等任务。利用 Se e ke r 软件提供的软件开发工具包（SD K），　动作捕捉数据可以通过定制化的数据接口实时导入 Grasshopper，在 Grasshopper 中实时获取标记点或刚体的位置信息并进行可视化（图 6）。*

引用格式 袁烽,柴华.面向批量定制的装配建筑数字建造技术体系——以装配式木构建筑创新为例[J].新建筑,2022(04):9-14.

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面向演示学习的人工 3C 装配动作光学采集系统研究

关键词

光学动作捕捉系统；示教学习；性能测试；系统优化

摘要

随着劳动力成本与消费需求的提升,消费电子类产品线生产效率与成本压缩要求也因此提高,实现3C 产品生产线的自动化迫在眉睫。传统的编程方法对于频繁更替的装配过程而言部署复杂,且针对精度要求较高的精密装配环节,难以用遥操作或示教器等方法完成,因此本文选择示教编程（Programming by demonstration,Pb D）的学习方法,直接通过学习操作工人的装配动作生成机器人运动轨迹。为了为演示学习过程提供完整准确的数据轨迹,首要任务就是对于操作者的装配动作实现高精度采集。

本文基于演示学习方法设计了一款针对人工 3C 装配背景的光学采集系统。通过 3C 装配工艺分析、性能测试选型、系统硬件设计、布局优化及预处理算法设计等环节,确定了光学采集系统最优布局参数,并确定了包含数据降噪、轨迹分段、缺失点填补的预处理算法框架。并利用 3C 装配中具有代表性的鼠标 PCBA 与鼠标外壳装配实验进行系统可用性与算法可行性验证,最终结果证明本文设计的面向演示学习的光学采集系统可以实现 3C 装配动作的准确采集。

本文对于实际 3C 手机装配流水线工艺分解,明确装配空间及装配所需的核心工作区域和采集性能评价指标；并根据不同类型动作捕捉设备的采集特点和适用范围。本文设计了光学动作采集系统系统化的硬件平台性能测试方案。除了静态评估外,在动态性能评估中还引入将应用于机床性能评估的轮廓误差概念用以评估装配轨迹的跟踪性能。并对于系统设计细节的参数进行优化性能评估,最终确定八目光学动作捕捉系统的空间布局设计。

此外,由于原始轨迹存在抖动与丢点的问题,因此在进行策略学习进行轨迹融合提取,利用预处理算法对原始数据进行降噪、分段、丢点数据填补处理,其中包括异常子检测、BP-AR-HMM 算法以及高斯过程回归算法,最终生成平滑数据进行下一步后处理操作。

本文的最后基于设计完成的面向示教学习的光学采集系统,对鼠标 PCBA、鼠标外壳的装配过程进行采集,利用预处理算法及策略学习方法,最终提取出光滑高效的演示示教轨迹,利用单臂串联机器人及自制双臂并联机器人实现装配过程的模拟,实现有效的人工经验迁移。

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本文考虑到手部动作要求较高采集精度，因此选择有标记点式动作捕捉设备进行系统设计及实验。

引用格式 曹芷琪.面向演示学习的人工 3C 装配动作光学采集系统研究[D].哈尔滨工业大学，2021.DOI：10.27061/d.cnki.ghgdu.2021.001118.

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人体上肢运动控制策略提取及应用

关键词

人体运动控制策略构建；双层优化；MPC 算法；控制策略映射

摘要

随着全球人口老龄化加剧和劳动力成本提升，社会对机器人的应用需求越发强烈。为更好地提供服务，机器人需要从工业现场走入日常生活之中。相较传统工业领域，日常生活环境动态特性强，导致基于预编程的机器人轨迹规划控制方法难以胜任任务需求。如何将人的控制策略传递于机器人，使其获得类人的控制行为，是提升机器人在动态环境中工作能力的关键。

人体控制系统由上层中枢神经系统与底层肌肉反射控制联合构成，其中包含的机理尚不明确，难以通过直接构建的方法描绘控制策略。通过优化控制框架建立人体运动控制系统是目前公认有效方法，在诸多实验中得到验证。本文基于优化框架就人体控制策略构建及提取方法展开研究，并将人的控制策略映射于机器人系统之中。具体工作如下：

（1）基于双层优化的人体运动控制模型构建及求解。首先通过反优化框架原理分析，给出人体运动控制策略的模型构建方法。然后利用 PSO 和 DC 算法，设计双层优化框架求解建立的人体运动控制模型，以提取人体上肢运动控制策略。

（2）基于 MPC 的人体运动控制策略学习。首先通过 MPC 算法原理分析，建立仿人体上肢运动控制的 MPC 预测模型。然后利用 PSO 算法，设计人体运动控制策略中目标函数到 MPC 预测模型中目标函数的间接映射方法。最后通过在 MPC 中加入反馈矫正，实现对 MPC 预测控制律的求解。

（3）将上肢运动控制策略映射于实际机器人控制系统中。首先，设计击球与移物两个验证实验，规定多个实验标准以确保执行任务时需要权衡目标冲突。随后分析 UR5 机械臂正逆运动学，搭建基于 ROS 系统与 MPC 算法的控制框架，详细介绍了实验平台搭建过程。最后就实验数据予以分析。

实验结果表明：本文提出的双层优化框架能有效提取人体上肢控制策略，且基于 MPC 的控制框架可有效地将人体控制策略传递给 UR5 机械臂。相较于直接映射方法，间接映射法可获取更适合机器人本体的控制策略。本文所提方法及实验结果可为构建机器人类人控制研究提供参考。

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图 4-5 运动捕捉系统与人体上肢 Marker 贴点示意图

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本实验采用被动式光学运动捕捉系统（Nokov，北京度量科技有限公司）记录实验者上肢运动学信息。该系统共含 8 个高清摄像机，捕捉频率为 50Hz，通过捕捉贴在人体手臂 Marker 点的反射光线，记录各 Marker 点在实验空间中的坐标信息。每组实验中，需在实验者的手臂关键解剖位置贴上 Marker 点（共计 13 个，如图 4-5 所示），以减少皮肤或肌肉相对运动产生的影响。

引用格式 周雅倩.人体上肢运动控制策略提取及应用[D].武汉理工大学，2022.DOI：10.27381/d.cnki.gwlgu.2022.001195.

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人与机器人共存中的位姿估计与碰撞检测

关键词

人机交互；位姿估计；碰撞检测；手臂运动；

摘要

提出了一种人与机器人共存中的位姿估计与碰撞检测方法。首先，利用光学 3 维动作捕捉系统获取标记点位姿信息，建立人体手臂的运动学模型。其次，针对工作空间中障碍物遮挡导致部分标记点位姿信息丢失的问题，将角度传感器获取的肘关节角度作为人体手臂运动学模型的输入，获取人体手臂末端位姿信息。再次，构建人体手臂和协作机器人的胶囊体模型，计算各胶囊体之间的最短距离，从而判断人机的相对位姿关系并实现碰撞检测。最后，通过 10 个人在不同人机共存场景下对人机位姿估计与碰撞检测方法进行评价。实验结果表明，本方法估计的人体手臂末端位置误差在 20 mm 以内，人机最短距离的最大误差为 14.53 mm，能够实现人机碰撞检测。

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图 2　光学 3 维动作捕捉系统工作空间

Fig.2　The workspace of optical 3D motion capture system

NOKOV 度量动作捕捉在研究中的应用摘录

光学 3 维动作捕捉系统相较于其他的室内定位技术具有精度高、实时性好等优点。本文采用 NOKOV 公司的光学 3 维动作捕捉系统分析手臂前臂和上臂的运动特性。该系统采用 8 个型号为 Mars2H、分辨率为 2048×1088、帧率为 340Hz 的红外高速摄像机，系统定位精度 为 0.02mm。通过不同相机对同一个标记点的空间运动图像进行采集，标记点反射回的红外光通过信号处理后由现场可编程门阵列 （FPGA）进行图像抓取和算法处理，获得反光标记点在镜头中的 2 维坐标。多个镜头通过 L 形标定框确立空间原点，接着通过 T 形标定框标定系统工作空间，从而获取每个镜头的具体位置，最终得到标记点的 3 维坐标。根据获取的 3 维坐标进行相关性分析，能够在工作空间中捕捉贴有标记点的移动物体的运动。

引用格式 黄沿江，汪子钦，张宪民等.人与机器人共存中的位姿估计与碰撞检测[J].机器人，2022,44（03）：281-290.DOI：10.13973/j.cnki.robot.210190.

链接

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巷道支护双臂机器人设计及自动控制研究

关键词

巷道支护双臂机器人结构设计；力学特性；运动学；运动规划；自适应神经网络非奇异性终端滑模控制

摘要

针对巷道支护智能化、无人化程度低，效率慢等缺点，将 W 钢带与锚杆配套使用，通过 W 钢带把分散锚杆联结形成一个整体支护结构。将锚杆对围岩的集中力转换为分布力，保证巷道围岩整体稳定性。巷道支护双臂机器人以履带式行走小车为本体，抓取梁机械臂为辅助支护，对钻臂进行研究；从而实现巷道支护自动化。对钻臂机械结构、运动学分析、松协调运动规划以及驱动空间控制算法进行了较为详细的研究。

基于巷道支护工艺流程，确定巷道支护双臂机器人驱动方式及总体布置，进行其本体结构设计，建立钻臂虚拟样机模型并进行不同工况仿真分析，得到其动态力及力矩。基于动力学分析结果对各关键零部件进行静态强度校核。

基于齐次变化矩阵，利用 D-H 参数法构建钻臂相邻连杆的坐标系，推导其正运动学方程；获得钻臂末端姿态与各关节变量关系。采用蒙特卡洛法求解抓取梁机械臂及钻臂工作空间。针对特殊构型的 6 轴机械臂逆运动学难以求取的问题，采用秃鹰搜索优化算法求解其非线性逆运动学方程。采用高精度测量仪红外动捕分析巷道支护双臂机器人基坐标关系，构建统一坐标系；推导巷道支护双臂机器人松协调运动约束方程；基于圆柱包络碰撞检测实时测量双臂最短距离，引入五次多项式规划巷道支护双臂运动轨迹。

针对液压缸速度及加速度难以测量，采用 Levant's 鲁棒微分器推导其运行过程中液压缸速度及加速度；针对系统中存在未建模项及外部干扰、采用 RBFNN 逼近未知模型信息；基于此提出一种用于巷道支护双臂机器人试验平台轨迹跟踪的自适应神经网络非奇异性终端滑模控制器；通过仿真分析验证其有效性及高性能。实现巷道支护双臂机器人试验平台驱动空间轨迹跟踪，进行巷道支护双臂机器人样机研制。根据实际工作情况，完成硬件选型，搭建巷道支护双臂机器人自动控制系统。基于 OPC 技术实现 Simulink 与 PLC 通讯，完成 Simulink、cSPACE 及 PLC 联合控制完成巷道支护双臂机器人协同支护实验及轨迹跟踪实验。实验结果表明：巷道支护双臂机器人相比现有支护技术，其智能化程度更高。所提自适应神经网络非奇异性终端滑模控制相比于 PID 控制最大跟踪和标准差分别下降了 50.86%、50.96%。

该论文有图 69 幅，表 12 个，引用格式 93 篇。

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图 3-9 基坐标标定

Figure 3-9 Base coordinate calibration

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本文采用红外动捕系统进行基坐标标定，4 个红外镜头分辨率为 20481088。由于 NOKOV 动捕系统在室内测量精度达到亚毫米级别，因而可以认为其测量出来红外标识点坐标为真实值。

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钻涨协同破岩系统设计及末端自主定位控制研究

关键词

钻涨协同破岩系统；自主定位；运动性能；定位误差补偿

摘要

针对硬岩巷道掘进工作时，综掘法机械刀具磨损严重，钻爆法安全性低，粉尘量大的问题，基于岩石抗拉强度只有抗压强度十分之一的特性，使用钻涨法可以有效破碎硬岩。目前，钻涨法在实际作业中机械化程度低，钻臂末端定位精度差，需要人工辅助调整。针对上述问题，本文提出一种高效协同、稳定可靠的钻涨协同破岩系统，基于仿真分析与试验验证，对钻涨协同破岩系统结构设计及末端自主定位控制进行研究，实现末端精确定位，提高工作效率。具体研究内容包括：基于钻涨协同作业工艺流程，进行钻涨协同破岩系统本体结构设计，为后续研究提供基础；在多体动力学中建立虚拟样机模型，探究不同工况下各关节动态力的变化；为验证结构设计合理性，基于有限元软件完成钻臂关键零部件的刚强度分析。

在钻涨协同破岩系统结构基础上，基于 D-H 法完成钻臂运动学建模，获取钻臂末端位姿与各关节运动量的关系，在机器人工具箱中验证所建模型的准确性，为自动化作业奠定基础；针对传统数值法求解逆运动学难以选取初始点的问题，基于多种群粒子群结合全局搜索算法进行求解，仿真结果表明总体计算误差较小，满足精确控制要求；引入五次 B 样条曲线规划液压缸运动轨迹，减少钻臂运行时产生的冲击。

针对钻臂末端定位误差影响因素较多，难以有效消除的问题，提出一种误差分级补偿方案。通过最小二乘法辨识几何参数得到钻臂实际运动学模型；基于悬臂梁公式，将钻臂视为伸缩式吊臂进行挠性变形计算；针对钻臂非几何参数误差，利用神经网络回归建立定位误差预测模型，为进一步提升预测精度，使用改进麻雀搜索算法优化神经网络，通过试验验证所提出算法的准确性。

为验证所提出误差补偿模型的有效性，搭建钻涨协同破岩系统试验平台，完成钻臂自动控制与误差补偿试验。试验结果表明，误差模型可以有效的修正定位误差，实现了钻臂自主定位与末端精确控制。

该论文有图 70 幅，表 17 个，引用格式 86 篇。

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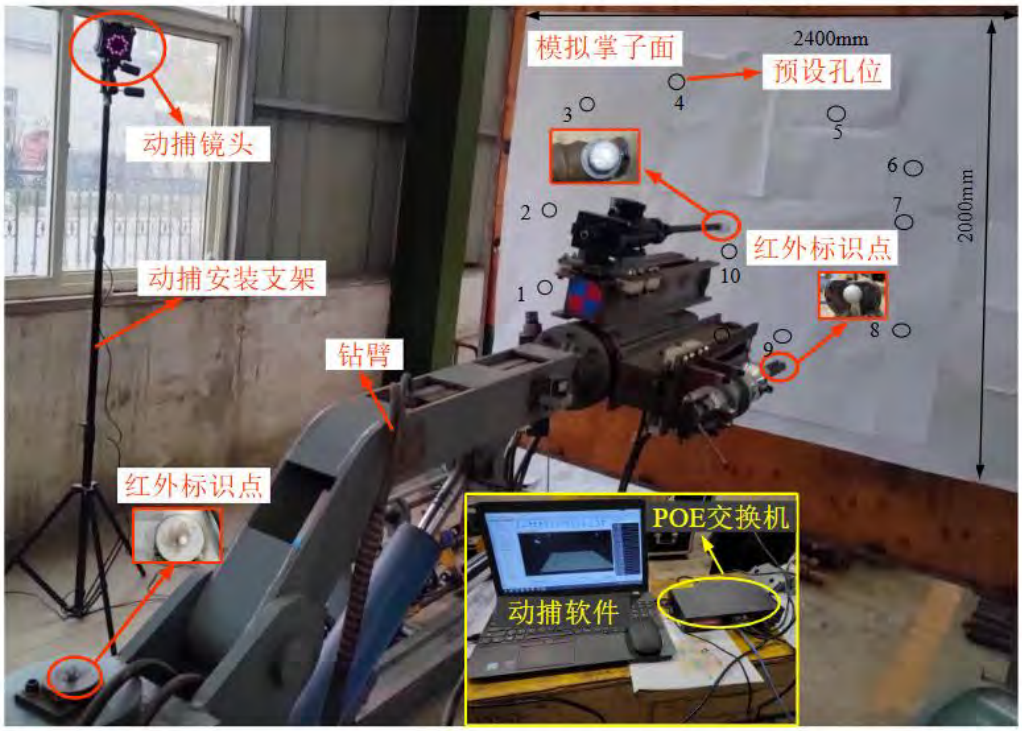

图 5-11 钻孔定位误差补偿试验系统

Figure 5-11 Drilling positioning error compensation test system

NOKOV 度量动作捕捉在研究中的应用摘录

为验证钻臂末端能否达到期望位置，本文使用 NOKOV 动作捕捉系统测量钻具实际位置。该系统主要包括红外动捕相机、红外标识节点、标定 T 型杆、POE 交换机以及上位机传输软件 seeker。

引用格式 束正强.钻涨协同破岩系统设计及末端自主定位控制研究[D].中国矿业大学，2023.DOI：10.27623/d.cnki.gzkyu.2023.000698.

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https://kns.cnki.net/kcms2/article/abstract?v=DFdco8Sly0I1F6suzyztFN9L9MWIWzsfnI6zlPy6D2r8jgZHxeIljMJPldI3eKzJqOL3Ld2hGkFKANAswkoWRYdLMwfubM5YGQs64rcVncVbBWs1Jy-7fg==&uniplatform=NZKPT&language=gb

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多旋翼飞行机械臂机体姿态抗扰动控制方法

关键词

多旋翼飞行机械臂；时变质心偏移；粒子群优化；参数整定

摘要

针对多旋翼飞行机械臂作业中存在的特有问题--欠驱动的多旋翼平台易受阵风、乱流等外部干扰，以及机械臂规划运动导致的系统内部扰动影响无人机姿态，提出了一种基于质心可变动力学模型的抗干扰控制方法，结合多刚体质心运动学分析手段，将内、外部扰动分解耦合至无人机动力学模型，构建融合机械臂时变质心偏移的四旋翼机体耦合非线性动力学模型，在降低一体化建模复杂度的同时兼顾模型精度。针对传统自抗扰控制（ADRC）参数整定复杂的难题，设计了基于粒子群优化算法（PSO）的参数整定方法，将优化参数应用于机体平台姿态控制器。仿真表明，所提方法使扰动估计值与实际扰动值的均方根误差（RMSE）降至 6.7%，姿态角波动幅值抑制方面相较于比例-积分-微分（PID）控制器、基于非线性扰动观测器的比例-积分-微分（NDOB-PID）控制器，分别提升 78%、73%。实物实验表明，在机械臂规划运动造成内部干扰的情况下，姿态角平均偏差范围为 4.02° ~ 9.65°。

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(a) 空中悬停　(b) 机械臂上下动作　(c) 机械臂左右动作

图 12　机械臂关节上下、左右动作

Fig.12　Vertical and horizontal motions of the robotic arm joint

NOKOV 度量动作捕捉在研究中的应用摘录

实验场地由装配 NOKOV 度量动作捕捉系统构成。首先，实验平台抵达作业空域后并悬停空中，机体平台保持水平。然后，设置滚转角、俯仰角、偏航角的期望值，并控制机械臂关节在（0^\circ \sim 90^\circ）范围内大幅度上下、左右动作（如图 12 所示）。将机械臂产生的转动的力、力矩作为对机体平台姿态稳定的干扰项，分析机械臂关节运动对机体姿态的耦合干扰抑制效果。

引用格式 孟帅,徐明兴,王俊林,等.多旋翼飞行机械臂机体姿态抗扰动控制方法[J/OL].信息与控制,1-12.https://doi.org/10.13976/j.cnki.xk.2025.2262.

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https://kns.cnki.net/kcms2/article/abstract?v=H8HwaL3t0AvjFCWOtuCTa4OFDMV0q9PBvuV7vfdC8lCo4EtiYQeiq4dDuDD1Ius-pn2WaH5wDfcvrrXFSKGL1k8QG-2kqSIkY3nLRka2quJ-AkLiBra_4UZy_suWdX4sBzLkUN9TaJJpY110zojzbukrwyWw24CZQLFm17oBdL82-OQYPM7mug==&uniplatform=NZKPT&language=CHS

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IV. Marine & underwater

A bilayer-coupled dynamic modeling method for mechanism-induced nonlinearity of a fully enclosed multi-axis wave energy converter

Keywords

Multi-axis wave energy converter, Cable-driven parallel mechanism, Dynamic modelin

Abstract

Multi-axis wave energy converters (WECs), which reach multi-axis power absorption through parallel mechanisms, have demonstrated the potential to generate more power than single-axis WECs. Unlike the widely researched hydrodynamic nonlinearity, the nonlinearity of the parallel mechanism used in multi-axis WECs remains largely unexplored. Consequently, a fully enclosed multi-axis WEC (FM-WEC) is introduced in this paper, where a cable-driven parallel mechanism (CDPM) is sealed within a waterproof shell, enabling the WEC to absorb power from multiple axes. First, the concept of the FM-WEC is proposed, and its bilayer-coupled dynamic model is established and decoupled in the frequency domain. Second, a theoretical exploration of the power and motion response is presented in the frequency domain. Thirdly, the nonlinearity of the CDPM in the FM-WEC is explored, and the nonlinearity of the CDPM is experimentally validated. Finally, a potential field method for analyzing the distribution of the nonlinearity of the CDPM is proposed, and the nonlinear effects on the motion and power responses of the FM-WEC are investigated. The results indicate that the nonlinearity of the CDPM results in a considerable deviation from the theoretical predictions, which provides inspiration for other multi-axis WECs based on parallel mechanisms.

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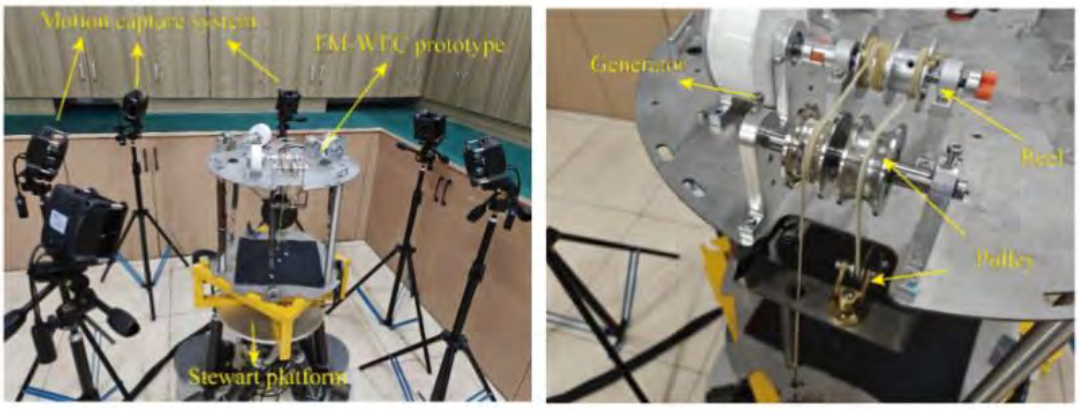

(a) Experimental arrangement (b) FM-WEC prototype

Fig. 8. Experimental setup of the FM-WEC prototype.

How NOKOV Contributes to the Research

44.2. Experimental validation of the dynamic model
To verify the dynamic model and influence of nonlinear effects on the FM-WEC, an experimental prototype of the FM-WEC was developed in this paper, as shown in Fig. 8. The prototype was securely mounted on a six-DOF Stewart platform, which directly generates motion to induce relative displacement between the outer floater and the inertial mass. The actual displacements of the Stewart platform and the prototype are then measured using a motion capture system. The motion capture system employed in this experiment is manufactured by NOKOV Science & Technology Co., Ltd. It consists of six infrared optical cameras (model: Mars 1.3H), reflective markers, and a data processing system. The reflective markers are attached to the object, and the infrared optical cameras actively emit infrared light, which is reflected by the reflective markers and subsequently captured by the camera array. Subsequently, the data processing system calculates the 3D coordinates of the reflective markers based on the vision localization. This allows the calculation of the position and orientation of the object using the coordinates of the attached reflective markers. Moreover, the mass of the inertial mass is 14.3 kg, the points of attachment of the three upper cables are uniformly distributed on a circle with a radius of 0.247 m on the upper platform and the fourth cable is vertically connected downward to the center of the lower platform. The vertical distance between the upper and lower points of attachment is 410 mm. The PTO stiffness is provided by linear springs, and PTO damping is provided through generator (connected to resistors) and the measured mechanical friction. Each cable has a PTO stiffness of 762 N/m, the damping of the upper three PTO are measured as 97.5 N·s/m, and that of the lower PTO is 30 N·s/m. Additionally, the preloading force on the lower cable is 121 N.

Citation Lu X, Gao Y, Han X, et al. A bilayer-coupled dynamic modeling method for mechanism-induced nonlinearity of a fully enclosed multi-axis wave energy converter[J]. Ocean Engineering, 2025, 342: 122741.

Link https://www.sciencedirect.com/science/article/abs/pii/S0029801825024242

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A Cable-Actuated Soft Manipulator for Dexterous Grasping Based on Deep Reinforcement Learning

Abstract

The growing interest in the flexibility and operational capabilities of soft manipulators in confined spaces emphasizes the need for precise modeling and accurate motion control. Conventional control methods encounter difficulties in modeling and involve intricate computations. This work introduces a novel deep reinforcement learning (DRL) control algorithm based on neural network modeling. Using the Whale Optimization Algorithm, an approximate dynamic model for the soft manipulator is established. The twin delayed deterministic policy gradient is employed for DRL control. Domain randomization is applied during pretraining in a simulated environment. The algorithm addresses issues related to dependency on measurement data quality and redundant mappings, outperforming other methods by 8–15 mm in control accuracy. The trained DRL controller achieves precise trajectory tracking within the soft manipulator's task space, enabling successful grasping tasks in various complex environments, including pipelines and other narrow spaces. Experimental results confirm the autonomy of our controller in performing these tasks without human intervention.

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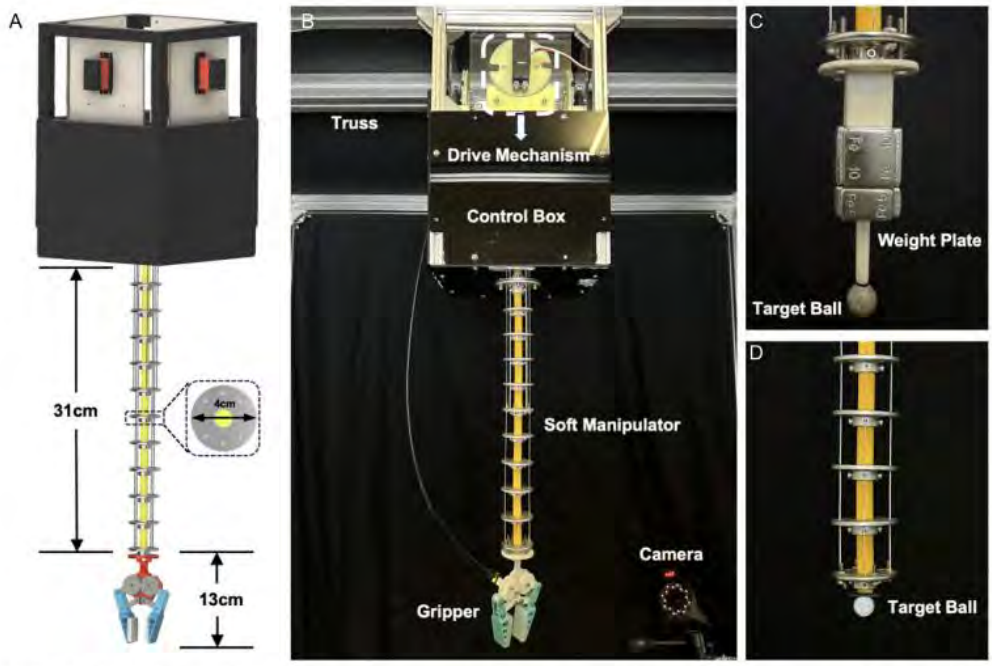

Figure 2. A) CAD of the soft manipulator. The soft manipulator consists of silicone rods and 10 metal discs, spanning a total length of 310 mm. Each over-line ring has a diameter of 40 mm, and the gripper measures 13 cm. B) System setup. The soft manipulator system is centrally mounted on a 120 × 120 × 150 cm aluminum frame, with six surrounding NOKOV cameras. C) Sampling method with load. The structure is 102 mm in height, weighing 75 g with the attached weight plate. An 8 mm target ball is fixed at the end, totaling a height of 110 mm. D) Sampling method without load. An 8 mm target ball is fixed at the end of the soft manipulator.

How NOKOV Contributes to the Research

The soft manipulator system is securely mounted at the central top of an aluminum profile frame measuring 120×120×150 cm. Around the perimeter of the aluminum frame, six NOKOV cameras are strategically positioned, forming the motion capture system. The soft manipulator system and the motion capture system together form the integrated experimental platform, securely mounted on a 135×135 cm vibration-damping platform through the aluminum profile frame.

Citation Zhou K, Mao B, Zhang Y, et al. A Cable-Actuated Soft Manipulator for Dexterous Grasping Based on Deep Reinforcement Learning[J]. Advanced Intelligent Systems, 2024, 6(10): 2400112.

Link

https://advanced.onlinelibrary.wiley.com/doi/full/10.1002/aisy.202400112?msockid=197ca6599a3365181986b53e9b1d649a

A Chordwise Bimodal Joint for Aerial-Aquatic Amphibious Flapping-Wing Robots

Keywords

Bio-inspired robots, mechanical design, foldablefin, manta ray-inspired robots.

Abstract

Biological manta rays alter the projected area of their pectoral fins during flapping, achieve different flapping strokes to adjust dynamic generation, such as holding, rising, sinking and rolling strokes. Manta ray-inspired robots possess high motion efficiency and stability, exhibiting broad prospects in underwater applications. A manta ray-inspired robot capable of projected area variations can gain more agility to adapt to complex environments. However, the fin structures of existing manta ray-inspired robots primarily serve to support and drive the flexible skin to flap, lacking the ability to vary the projected area. To achieve diverse flapping strokes, robots typically rely on multiple servos and complex algorithms to adjust each servo's motion parameters. In this article, we propose a foldable fin for manta ray-inspired robots, structurally varies the robot's span to adjust dynamic generation under simple control. The foldable fin is designed by linkage mechanisms, where three foldable modules are modularly meshed through tooth profiles, enabling synchronized folding and extending along a carbon spar. These design achieve a weight of 95 g with high stiffness, and a 78.75% foldable ratio with rapid operation. The kinematics of the foldable fin are modeled to describe different strokes. Underwater tests demonstrate that the maximum length of the foldable fin exhibits significant increase in lift and thrust compared to its minimum length in symmetric strokes, while asymmetric strokes exhibit significant adjustments in dynamics. Swimming validations further confirm the propulsion capability of the foldable fin, highlighting its potential to enhance the agility of manta ray-inspired robots.

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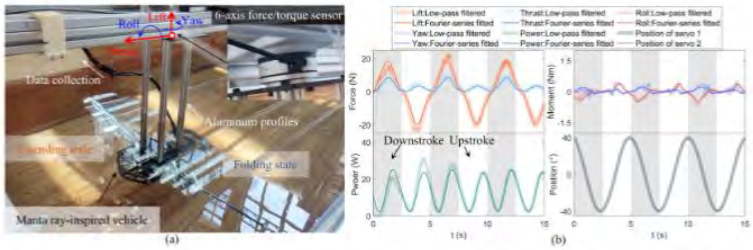

Fig. 6. Underwater tests for dynamic generation analysis. (a) The manta ray-inspired robot is fully submerged in water and fixed to the frame by a 6-axis force/torque sensor. (b) Measured data are filtered by a low-pass filter to remove the high-frequency noise, and then fitted by a 6-order Fourier series as periodic functions to reduce the influence of random disturbances during testing.

How NOKOV Contributes to the Research

In addition, the robot's aquatic swimming performance is evaluated based on the NOKOV Motion Capture(see Fig. 9(b)). The amphibious flapping-wing robot operates at a flapping fre-quency of 0.15 Hz, achieving a maximum swimming velocity of 0.13 m/s with an equivalent current consumption of around 1.8 A. These results suggest that the robot is capable of operating for 22 min using a little 650 mAh battery. An outdoor swimming test confirms that the robot can maintain stable forward motion over a distance of 30 m.

Citation Y. Xiang, L. Gu, Z. Gong, B. Tao and H. Ding, "A Chordwise Bimodal Joint for Aerial-Aquatic Amphibious Flapping-Wing Robots," in IEEE/ASME Transactions on Mechatronics, doi: 10.1109/TMECH.2025.3602143.

Link https://webofscience.clarivate.cn/wos/woscc/full-record/WOS:001566819900001

A Fully 3D-Printed Tortoise-Inspired Soft Robot with Terrains-Adaptive and Amphibious Landing Capabilities

Keywords

3D-printed robots, amphibious landing, biomimetic robots, soft robots, terrains-adaptive landing

Abstract

Terrain adaptation and amphibious landing pose the greatest challenges for soft amphibious robots. Based on the principles of tortoises, this paper presents a fully 3D-printed soft amphibious robot with four pneumatic bionic legs that are capable of bending in three dimensions. The gaits of the robot are described in six different ways and a dynamic model is developed for its control. In addition to linear motion (0.97 BL s−1) and turning (25.4° s−1) on rigid terrain, the robot can also maneuver on various surface conditions (such as hills, gaps, smooth slopes, gravel, sand, muddy terrain, and water), and even make an amphibious landing. These properties, together with the soft amphibious robot's continuous obstacle avoidance capabilities, high load-carrying capacity (28 times its own weight), low cost, and high camouflage, allow for a wide variety of applications.

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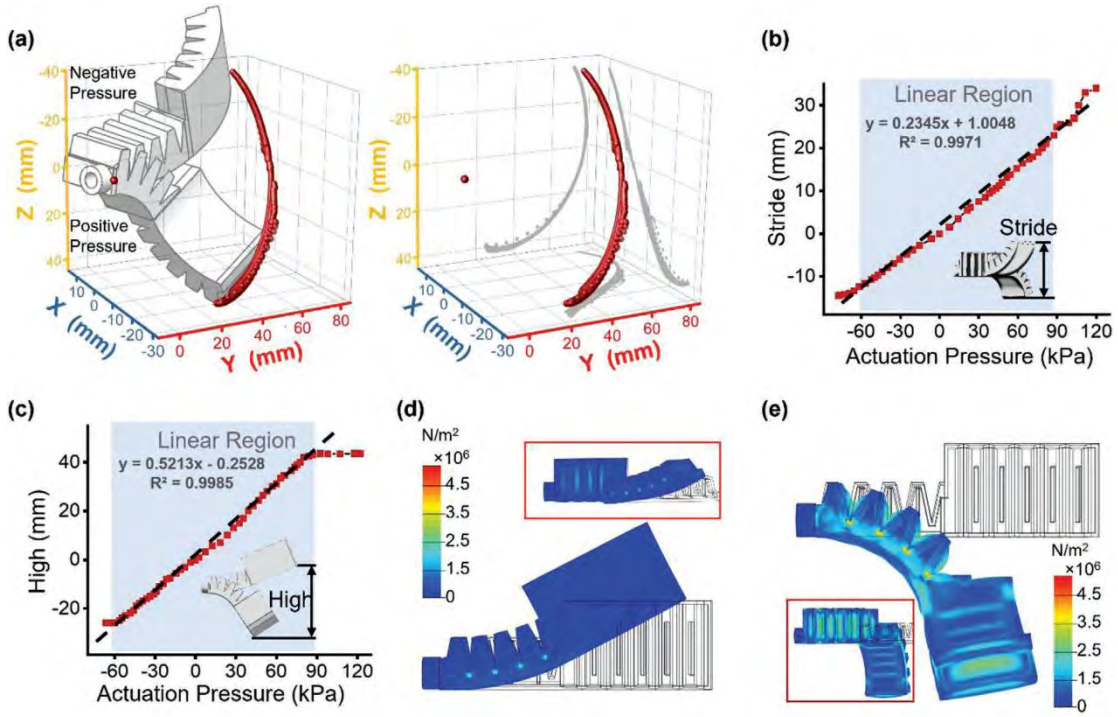

How NOKOV Contributes to the Research

The bionic leg's 3D motion trajectory was tracked with motion capture technology (NOKOV, China). Arduino Uno (Qixingchong Co., China), relays (Risym Co., China), air compressor (−90 to 200 kPa, customized) and valves (Shenglong Co., China) were used to control BASR. A Go-pro and an Apple iPhone 11 were used to record BASR's movements.

Citation Wu M, Xu X, Zhao Q, et al. A fully 3D-printed tortoise-inspired soft robot with terrains-adaptive and amphibious landing capabilities[J]. Advanced Materials Technologies, 2022, 7(12): 2200536.

Link https://onlinelibrary.wiley.com/doi/10.1002/admt.202200536

Aqua-Splat: Physically-Informed Sonar-Camera Gaussian Splatting for Underwater 3D Reconstruction

Keywords

Gaussian splatting, acoustic-optic vision, sensor fusion

Abstract

Differentiable Gaussian Splatting (GS) has emerged as a powerful paradigm for scene representation, enabling efficient rendering and real-time editing. However, existing GS-based methods, which rely mainly on clear visual images, perform poorly in underwater environments due to camera distortions such as light absorption and backscattering. In contrast, acoustic sensors like Forward Looking Sonar (FLS) offer superior penetration and robustness in such conditions. To leverage the complementary merits of visual and FLS images, we propose a novel GS framework customized for underwater scenarios, termed Aqua-Splat, for robust and accurate underwater perception. It ensures physically consistent reconstruction by incorporating the sonar wave propagation modeling in the image formation process. Moreover, we propose a volume rendering technique for sonar image synthesis, achieving similar speed to visual rendering. Additionally, we introduce a sonar-guided densification strategy to optimize the scene representation. Through extensive experiments on both simulated and datasets from the lab pool, we demonstrate that Aqua-Splat significantly improves image synthesis and 3D scene reconstruction in challenging underwater environments, outperforming existing methods in terms of both geometric accuracy and photometric fidelity. The code of Aqua-Splat will be open-sourced later for the community.

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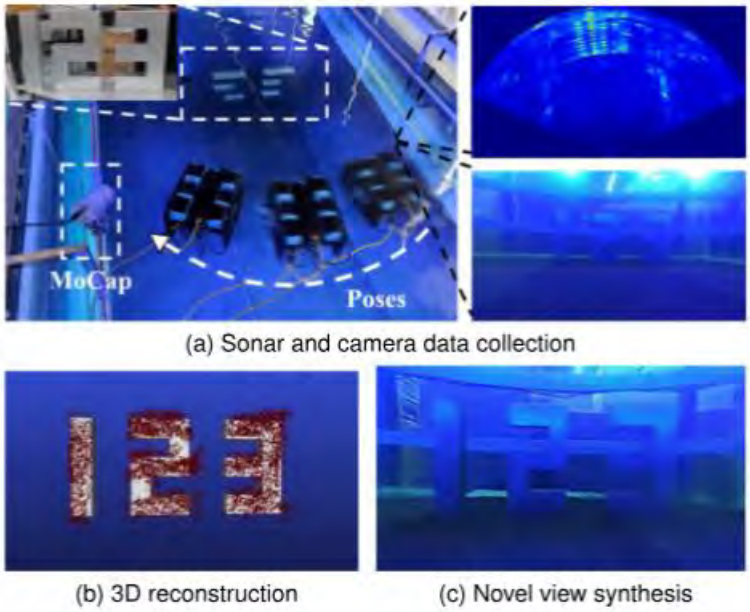

Fig. 1. **System setup, reconstruction and novel view synthesis by Aqua-Splat.** (a) Data collecting in underwater scenes. We use a ROV to collect visual and sonar data in the lab pool. An underwater motion capture system (MoCap) is used to obtain the ROV's poses. (b) 3D reconstruction of the underwater scene by Aqua-Splat. (c) Novel view synthesis of the underwater scene by Aqua-Splat.

How NOKOV Contributes to the Research

B. Experiments in the Lab Pool
Apart from the simulator experiments, we also conduct experiments using a ROV in a lab pool. The Bluerov2 robot equipped with a ZED2 stereo camera and an Oculus m750 d imaging sonar was used for the experiment, as shown in Fig. 8(a). Camera and FLS are well-calibrated underwater before experiments,the details of which follows the method in \[22]. We used hand-eye calibration to estimate the 3-DoF relative pose (x, y,yaw) between the sonar and camera, then manually measured the z-axis offset. Given the sonar is closely mounted to the camera, roll and pitch are negligible, resulting in a full 6-DoF relative pose. The tank is about 3.3 m in width and 6.6 m in length. We constructed three metal models in the shapes of numbers "1","2", and "3'" and placed them in the tank. A motion capture system NOKOV equipped with 12 underwater cameras was mounted upside around the tank, which provided the GT pose of the underwater robot, as shown inFig.8(b). The sonar image denoising procedure follows the method proposed in \[8]: frst, a trained Swin-Conv-Unet net-work (SCUNet)\[32] is applied to denoise the original sonar images. Then, a background image (obtained from object-free sonar frames using SCUNet)is subtracted to suppress staticn oise.

Citation Ling Z, Feng Y, Meng A, et al. Aqua-Splat: Physically-Informed Sonar-Camera Gaussian Splatting for Underwater 3D Reconstruction[J]. IEEE Robotics and Automation Letters, 2025.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001594944700012

Buoyancy-gravity optimized triboelectric nanogenerators via conductive 3D printing for robust wave energy harvesting

Keywords

Ocean energy, Triboelectric nanogenerator, Float stability, Conductive 3D printing, Hydrodynamic simulation

Abstract

Triboelectric nanogenerators (TENGs) represent a promising approach for large-scale harvesting of ocean wave energy. However, the design optimization of TENGs for wave energy harvesting remains underexplored, especially in terms of maximizing energy conversion efficiency through theoretical analysis. In this study, we present a novel cylindrical pellet-based triboelectric nanogenerator (CP-TENG) design, fabricated using multi-material and conductive 3D printing. This design optimizes the balance between the center of gravity and buoyancy for enhanced energy harvesting efficiency. The optimal float design was determined through hydrodynamic simulations and infrared optical tracking. Wave energy harvesting tests were conducted in a 4 × 45 m wave tank, demonstrating the CP-TENG's ability to power 2000 series-connected LEDs. The system exhibited remarkable durability, operating continuously for 120 hours, and proved highly adaptable to waves with varying frequencies and amplitudes. Importantly, the CP-TENG demonstrated significant potential for battery-free, long-range wireless communication, offering a promising solution for next-generation ocean monitoring systems.

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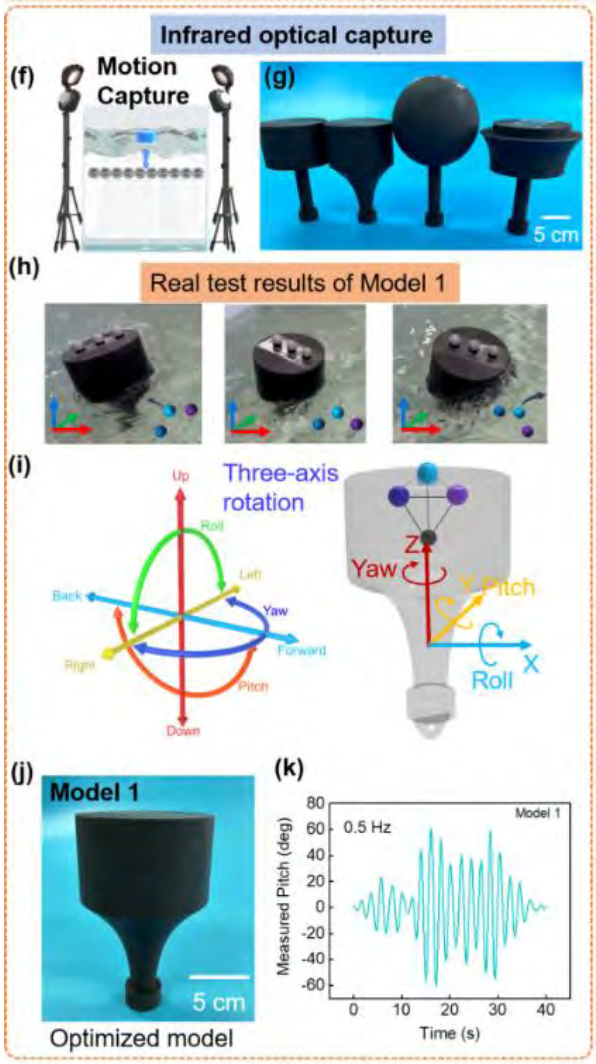

How NOKOV Contributes to the Research

The IOCS system used for testing was constructed with the assistance of NOKOV company. In this study, we selected four high- pixel (1.3-megapixel), high-resolution (12801024), low-latency, wide-angle (57◦ 44◦) capture lenses to form the IOCS system.

Citation Su E, Xu S, Wang Z, et al. Buoyancy-gravity optimized triboelectric nanogenerators via conductive 3D printing for robust wave energy harvesting[J]. Materials Science and Engineering: R: Reports, 2025, 164: 100953.

Link https://www.sciencedirect.com/science/article/abs/pii/S0927796X25000300

Cooperative Path Following Control of Multiple Underactuated USVs with Experimental Validation

Keywords

underactuated surface vehicle, cooperative path following, robust control

Abstract

This paper investigates cooperative path-following control for multiple underactuated Unmanned Surface Vehicles (USVs) operating in the presence of disturbances. A distributed coordination framework is developed to assign individual desired paths to each of the \\(n \\) USVs while preserving the overall formation pattern. Furthermore, we construct a backstepping-based path-following controller tailored for USVs, which guarantees that tracking errors converge to a small neighborhood and ensures global boundedness of the closed-loop system. A saturation function and disturbance observers are incorporated to improve the controller's resilience to external disturbances. The effectiveness of the proposed controller is demonstrated through both simulation and real-world experiments.

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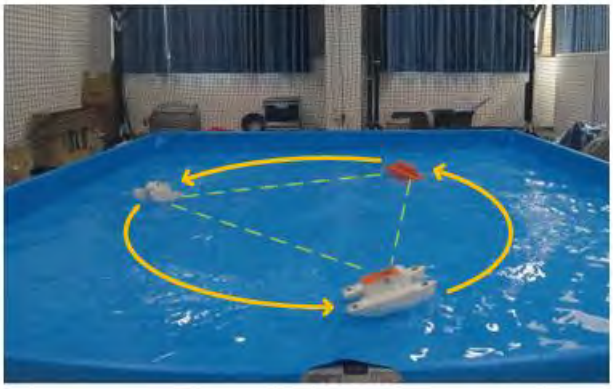

Fig. 10. A triangular formation of USVs circumnavigating a circular path.

How NOKOV Contributes to the Research

B. Experimental Setup We conduct experimental verification at the Artificial Intelligence and Robotics Center (AIRC) of Shanghai JiaoTong University. We set up a 4 m × 4 m indoor pool and3D-printed our small vessels. Due to space limitations on the vessels, we use a NOKOV motion capture system for state measurement. The experimental setup is shown in Figure 7.

Citation Zeng R, Duan K, Li E, et al. Cooperative Path Following Control of Multiple Underactuated USVs with Experimental Validation[C]//2025 IEEE Conference on Control Technology and Applications (CCTA). IEEE, 2025: 327-332.

Link

https://ev.docapi.xyz/app/doc/?docid=cpx_M63d76aa9199dcf77f40M6ad810178163219&pageSize=100&index=1&searchId=7a10e0309a11447a81d98ea063d4762e&resultsCount=1&usageZone=resultslist&usageOrigin=searchresults&searchType=Quick

Deep-learning-assisted triboelectric whisker for near field perception and online state estimation of underwater vehicle

Keywords

Underwater perception, Triboelectric nanogenerators, Whisker sensor, Self-powered, Deep learning

Abstract

Agile near field perception remains a challenge for underwater vehicles, which could significantly enhance their capability of online state estimation. Harbor seals have evolved a whisker array that can accurately measure and identify environmental information in their surroundings. Inspired by the "smart" whiskers of harbor seals, the study has designed a deep learning-assisted bionic underwater triboelectric whisker sensor (UTWS) to passively perceive diverse hydrodynamic flow fields, including omni-directional steady flow and wakes induced by bluff body upstream. The device mainly comprised an elliptical whisker shaft with a high-aspect-ratio of 0.403, four flexible triboelectric sensing units mimicking the nerve in the follicular sinus complex, and a flexible corrugated joint imitating the surface skin of marine organisms' cheeks. The UTWS demonstrated impressive advantages of rapid response times of 21 ms, high sensitivity of 1.16 V/m.s − 1, high signal-to-noise-ratio of 61.66 dB. By implementing deep learning analytics to process the multi-channel signals, the underwater vehicle equipped with the UTWS can accomplish online velocity estimation proficiently, with an approximate root mean square error of approximately 0.093 in the verification case. Thus, this UTWS-based, deep-learning-assisted perception could become a promising tool for integration with underwater vehicles in the local navigation tasks.

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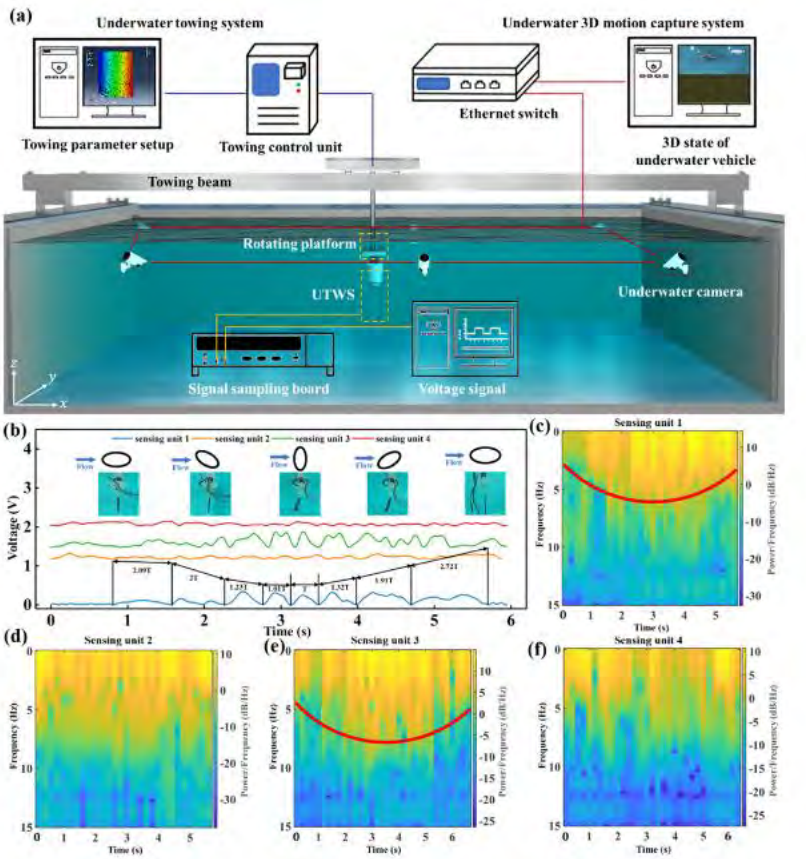

Fig. 3. Application demonstration of the UTWS in multi-directional hydrodynamic sensing. a, Basic structures of the experimental setup, including a signal measurement system, an underwater towing system and an underwater motion capture system. b, Characteristics of voltage curves of four sensing units in the process of rotating motion. c, d, e, f, Power spectral density of the output voltages of four sensing units.

How NOKOV Contributes to the Research

The 3D position and speed of the ROV were acquired using a commercial motion capture system called Nokov, as depicted in Fig. 3a and Supplementary Fig. 5.
5.3. Underwater 3D motion capture system Fig. 3(a) and Supplementary Fig. 3 illustrate the underwater motion state acquisition using an optical motion capture system by Nokov, a Chinese manufacturer. This motion capture system met the most demands of the underwater 3D motion capture. This system, incorporating six motion capture cameras, measured the position, velocity, and acceleration of underwater vehicles.

Citation Peng Xu, Jianhua Liu, Bo Liu, Yuanzheng Li, Hao Jin, Zhaoyang Mu, Tangzhen Guan, Guangming Xie, Hao Wang, Minyi Xu,Deep-learning-assisted triboelectric whisker for near field perception and online state estimation of underwater vehicle,Nano Energy,Volume 129, Part A,2024,110011,ISSN 2211-2855, https://doi.org/10.1016/j.nanoen.2024.110011.

Link https://www.sciencedirect.com/science/article/abs/pii/S2211285524007614

Deep-Learning-Assisted Triboelectric Whisker Sensor Array for Real-Time Motion Sensing of Unmanned Underwater Vehicle

Keywords

triboelectric nanogenerators, underwater perception, whisker sensor array

Abstract

Aquatic animals can perceive their surrounding flow fields through highly evolved sensory systems. For instance, a seal whisker array understands the hydrodynamic field that allows seals to forage and navigate in dark environments. In this work, a deep learning-assisted underwater triboelectric whisker sensor array (TWSA) is designed for the 3D motion estimation and near-field perception of unmanned underwater vehicles. Each sensor comprises a high aspect ratio elliptical whisker shaft, four sensing units at the root of the elliptical whisker shaft, and a flexible corrugated joint simulating the skin on the cheek surface of aquatic animals. The TWSA effectively identifies flow velocity and direction in the 3D underwater environments and exhibits a rapid response time of 19 ms, a high sensitivity of 0.2V/ms−1, and a signal-to-noise ratio of 58 dB. The device also locks onto the frequency of the upstream wake vortex, achieving a minimal detection accuracy of 81.2%. Moreover, when integrated with an unmanned underwater vehicle, the TWSA can estimate 3D trajectories assisted by a trained deep learning model, with a root mean square error of ≈0.02. Thus, the TWSA-based assisted perception holds immense potential for enhancing unmanned underwater vehicle near-field perception and navigation capabilities across a wide range of applications.

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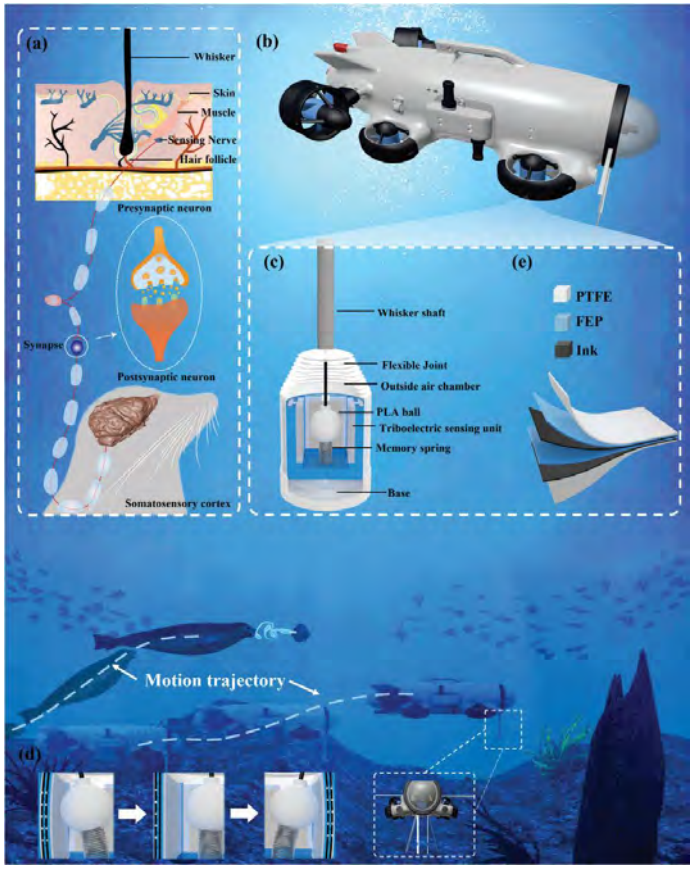

How NOKOV Contributes to the Research

To further explore the perception capability of TWSA, four TWSAwere integrated with a remotely operated vehicle (ROV) to testits ability to detect front obstacles and evaluate motion locationin FigureS1 (Supporting Information). The ROV's spatial co-ordinates and velocity were measured using a commercial mo-tion capture system called Nokov.

Citation Liu B, Dong B, Jin H, et al. Deep-Learning-Assisted Triboelectric Whisker Sensor Array for Real - Time Motion Sensing of Unmanned Underwater Vehicle[J]. Advanced Materials Technologies, 2025, 10(3): 2401053.

Link https://onlinelibrary.wiley.com/doi/10.1002/admt.202401053

Design and Control of a 6-DOF Fully Actuated Aerial-Aquatic Robot with Thrust Vectoring

Abstract

Single-medium, multi-degree-of-freedom robots often face limitations in aerial-aquatic tasks due to structural and weight constraints, which compromise their mobility in both air and water. To address this, we introduce a 6-degree-of-freedom fully actuated aerial-aquatic robot that employs thrust vectoring for enhanced performance. This innovative design incorporates four servos and four motors to facilitate coordinated operation. In air mode, the robot achieves decoupled control of attitude and position through servo angle feedforward compensation combined with dual-loop control. In underwater mode, it ensures high maneuverability by utilizing a dynamic model similar to a "weightless" state, employing single-loop control. Experimental results demonstrate that the robot can perform fully actuated movements in both air and water, successfully navigate the air-water boundary, and deploy sensors on inclined surfaces. These capabilities highlight the robot's significant future application prospects.

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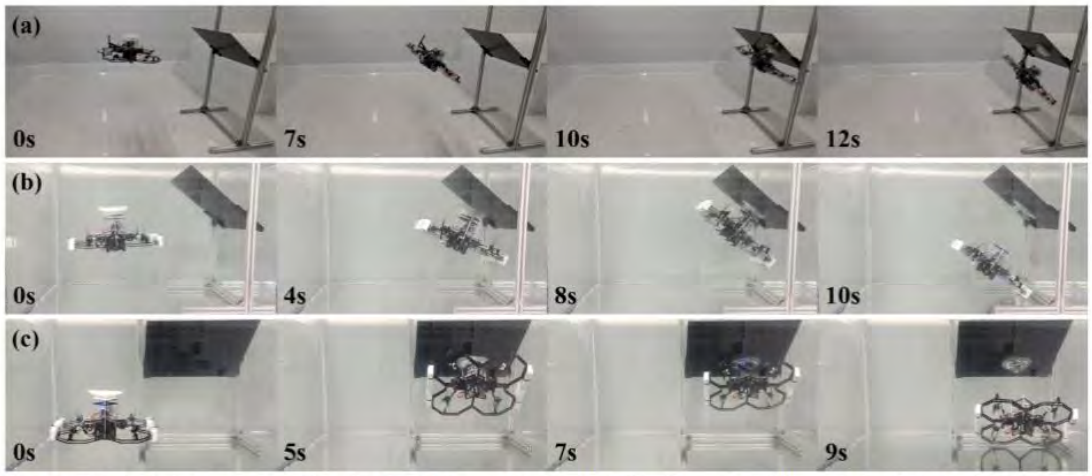

Figure 7. The robot deploys a sensing module in the air and underwater. (a) The robot deploys the sensing module on an inclined plane by adjusting its pitch angle in the air. (b) The robot deploys the sensing module on an inclined plane by adjusting its pitch angle underwater. (c) The robot deploys the sensing module on an inclined plane by adjusting its roll angle underwater.

How NOKOV Contributes to the Research

Fig. 7(a)illustrates the robot executing this process in the air. The robot first flies to the vicinity of the attachment plane, orienting its symmetric surface perpendicular to the attachment plane. While hovering, the robot adjusts its pitch angle to match the inclination of the attachment plane, ensuring the sucker surface remains parallel to it. Maintaining this pitch angle, the robot slowly approaches until it contacts the attachment plane, at which point the sucker adheres to the surface. After the robot departs, the sucker remains on the plane. Thissensor deployment experiment in the air relies on an aerial motion capture system(NOKOVMotion Capture, China)to provide positional data, with the flight trajectory and attitude angle adjustments programmed previously.When the robot approaches the attachmentplane, the opaque plane blocks the camera's recognition of the reflectivemarkerson the robot, causing instability when flying below the plane and colliding with the aluminum structure when leaving after deployment. This can be solved by replacing the positioning system, such as onboard ultra wide band (UWB) sensors.

Citation B. Tian, Y. Liu, X. Ren, D. Chen, Z. Zuo and L. Wen, "Design and Control of a 6-DOF Fully Actuated Aerial-Aquatic Robot with Thrust Vectoring," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 9099-9106, doi: 10.1109/IROS60139.2025.11246426.

Link https://ieeexplore.ieee.org/document/11246426

Design and Implementation of a Biomimetic Underwater Robot Propulsion System Inspired by Bullfrog Hind Leg Movements

Keywords

bionic underwater robot; bullfrog hind legs; multi-linkage mechanism;motion capture

Abstract

Underwater propulsion systems are the fundamental functional modules of underwater robotics and are crucial in intricate underwater operational scenarios. This paper proposes a biomimetic underwater robot propulsion scheme that is motivated by the hindlimb movements of the bullfrog. A multi-linkage mechanism was developed to replicate the "kicking-and-retracting" motion of the bullfrog by employing motion capture systems to acquire biological data on their hindlimb movements. The FDM 3D printing and PC board engraving techniques were employed to construct the experimental prototype. The prototype's biomimetic and motion characteristics were validated through motion capture experiments and comparisons with a real bullfrog. The biomimetic bullfrog hindlimb propulsion system was tested with six-degree-of-freedom force experiments to evaluate its propulsion capabilities. The system achieved an average thrust of 2.65 N. The effectiveness of motor drive parameter optimization was validated by voltage comparison experiments, which demonstrated a nonlinear increase in thrust as voltage increased. This design approach, which transforms biological kinematic characteristics into mechanical drive parameters, exhibits excellent feasibility and efficacy, offering a novel solution and quantitative reference for underwater robot design.

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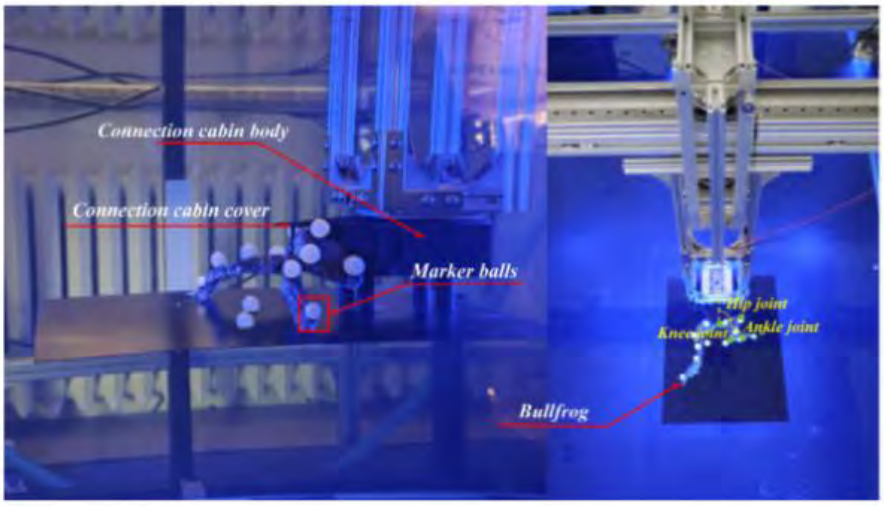

Figure 3. Schematic diagram of the motion capture experiment on a real bullfrog.

How NOKOV Contributes to the Research

The NOKOV Motion Capture System is employed to conduct motion capture investigations, utilizing a passive marker-based optical capture solution. Six NOKOV underwater motion capture cameras are installed on the experimental platform, with one camera installed at each endpoint and midpoint along the two shorter sides of the tank. In order to prevent measurement errors caused by inter-medium refraction and achieve precise capture and analysis of the experimental subject's motion posture in water, NOKOV's underwater motion capture cameras were chosen, as the difference in refractive indices between air and water can affect the accuracy of motion data collection. The camera lens and active light source are fully submerged in water. The experimental subject's fixed position in the water is configured to be adjustable in order to facilitate the installation of the experimental subject's fixation components and to capture the movement of marker points by as many motion capture cameras as feasible during motion capture experiments. Tracks are installed along the long sides of the pool using 40 mm × 40 mm European standard aluminum profiles. Movable crossbeams, which are constructed from 40 mm × 80 mm European standard aluminum profiles, are mounted on the tracks. The crossbeam is equipped with a connection platform that can be adjusted in position using a hand-crank screw shaft and tracks. The connection platform is connected to the vertical support structure that secures the experimental subject. The marked points on the experimental subject can be captured by as many motion capture cameras as possible by manually adjusting the screw rod to alter the position of the movable experimental object fixation frame.

Citation Chu, Y., Wang, Y., Fu, Y., Ma, M., Zhong, Y., & Yu, T. (2025). Design and Implementation of a Biomimetic Underwater Robot Propulsion System Inspired by Bullfrog Hind Leg Movements. Biomimetics, 10(8), 498.

Link

https://libresource.chd.edu.cn/https/443/cn/clarivate/webofscience/yitlink/wos/woscc/full-record/WOS:001557871200001

Design and Performance Study of a Six-Bar Mechanism Underwater Robot Based on Cownose Ray Bionics

Keywords

cownose ray robot, bionic mechanism design, kinematic analysis, underwater tests

Abstract

This paper focuses on the formidable challenges that underwater robots encounter in complex marine environments. To address these issues, inspired by the cownose ray, an innovative scheme is proposed, utilizing four six-bar mechanisms to mimic its pectoral fin movement. Subsequently, the paper elaborates on the design, computation, and simulation of the bionic pectoral fin mechanism. A Watt-type six-bar mechanism is adopted, and by axially overlaying two scaled-identical mechanisms and setting a phase difference, the pectoral fin waving of the cownose rays is simulated. SolidWorks and ADAMS are employed for precise modeling and simulation. Following this, an experimental prototype is constructed, with the rod assembly produced by subtractive machining. Motion capture and six-dimensional force experiments are then conducted to evaluate its motion dynamics and propulsion efficacy. The experimental results demonstrate that when the two pectoral fins on either side flap synchronously or inversely, the robot can generate varying thrust, lift, and lateral forces, enabling smooth advancement and turning. These findings validate the feasibility and efficacy of bionic design, offering innovative concepts and methodologies for underwater robot development.

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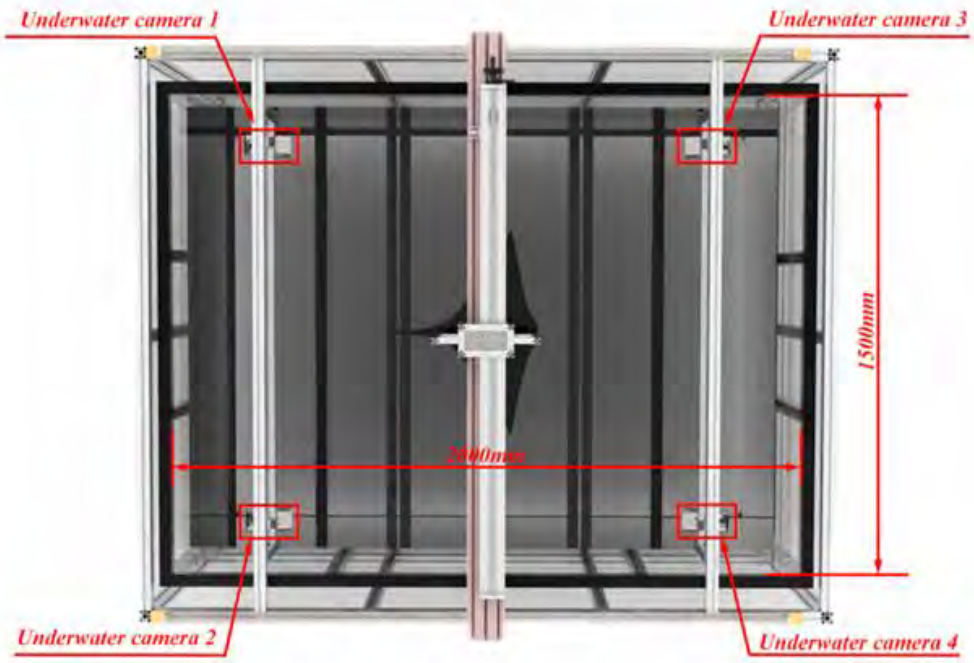

Figure 9. Distribution of motion capture cameras in the overhead platform view.

How NOKOV Contributes to the Research

The NOKOV Motion Capture System was employed in the motion capture experiment to record and analyze the movements of the experimental prototype of the bionic cow nose ray's motion mechanism. This experiment employed a passive marker-point optical motion capture system, with four NOKOVMotion Capture Cameras positioned at each corner of the pool to ensure the maximized capture range, as shown in Figure 9. In the motion capture experiments, to eliminate deviations in the skeletal motion data of the experimental prototype of the bionic cownose ray caused by the differing refractive indices of air and water, NOKOV's underwater motion capture camera was employed, with the lens fully submerged to avert errors arising from the transition between media.
At the beginning of the experiment, the drive servo of the bionic mechanism on the side of the marker was energized, and the motion data of the bionic mechanism was acquired by NOKOV's underwater motion-capture camera and communicated to the computer.

Citation Chu, Y., Wang, X., Hao, T., Fu, Y., Duan, Y., & Yu, T. (2025). Design and Performance Study of a Six-Bar Mechanism Underwater Robot Based on Cownose Ray Bionics. Journal of Marine Science and Engineering, 13(6), 1156.

Link https://www.mdpi.com/2077-1312/13/6/1156

Dynamic behavior and energy flow of floating triboelectric nanogenerators

Keywords

Blue energy, Triboelectric nanogenerator, Six degrees of freedom test, Kinetics analysis, Optical motion capture system

Abstract

The comprehension of the dynamic behavior and energy flow characteristics of triboelectric nanogenerators on water is a prerequisite for enhancing wave energy conversion efficiency and output performance, yet these data have always been lacking, impeding their progress in harnessing blue energy. Herein, a series of meticulously conducted experiments aim to unveil the interaction between water waves and the geometrical structures of floating triboelectric nanogenerators (F-TENGs). The six degrees of freedom (6DoF) information of various F-TENGs under wave excitation is received for the first time by employing the new high-tech Infrared Optical Capture System and precision numeric analysis. Based on statistical data from 118 research papers, the most universally applicable modes/parameters are systematically explored, as well as the non-rigid body models. The six-dimensional kinematic radar matrices and energy gradient curves, peeled from the calculation and statistics of the 6DoF data, have comprehensively illuminated the dynamic behavior and energy flow of F-TENGs while interacting with water waves. These results can serve as an enlightening framework for structural design and facilitate the optimization of F-TENG in harnessing blue energy.

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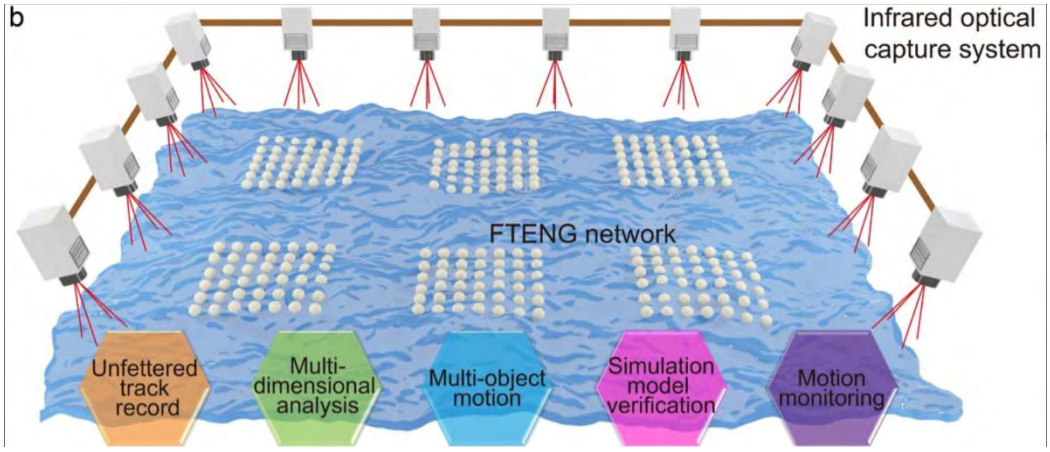

How NOKOV Contributes to the Research

The IOCS system used for testing was constructed with the assistance of NOKOV Corporation, utilizing their NOKOV Motion Capture System, which comprises four high-definition cameras, a splitter, a three-axis gimbal, markers, and other components. Among these components, the lenses play a central role in the entire IOCS system, as their resolution and field of view determine the effectiveness and precision of F- TENG motion tracking.
Data decoding for the marker points is performed using NOKOV' s specialized software Suixing and subsequent kinematic calculations are carried out in collaboration between Matlab and Origin.

Citation Xu S, Zhang J, Su E, et al. Dynamic behavior and energy flow of floating triboelectric nanogenerators[J]. Applied Energy, 2024, 367: 123468.

Link https://www.sciencedirect.com/science/article/abs/pii/S0306261924008511

Experimental study on 3D hydroelastic response of entire long span submerged floating tunnel with catenary-mooring constraint and perpendicular regular waves action

Keywords

Submerged Floating Tunnel, Hydroelasticity, Entire 3D Response, Catenary-Mooring, Experimental Study, Perpendicular Regular waves

Abstract

Clarifying the hydroelastic dynamic response of submerged floating tunnel (SFT) is an important prerequisite for its safety design. Currently, most of the research focuses on theoretical analysis and numerical simulation, and lack of relevant 3D model tests. In this series of studies, 3D entire long span experiments were carried out to systematically study the hydroelastic response mechanism of the SFT. The practical end constraint, the elastic deformation along the tunnel and the coupling effect between the tube and the mooring system was entirely experimentally simulated. Taking the catenary as the mooring system and perpendicular regular waves action, this paper analyzes the 3D hydroelastic response characteristics of the submerged floating tunnel under different wave periods and end pretension conditions, the tube displacement, acceleration and mooring tension along the tunnel were carefully measured. The test results show that the wave period has a significant effect on the displacement and acceleration of the tube, especially when the wave period is close to the structure natural period, the amplitude reaches the maximum, and the displacement and acceleration of the tube reach the maximum at the mid-span. Both horizontal and vertical displacement and acceleration increase first and then decrease with increasing the relative frequency f/fN and KC number. With the increase of the end pretension, the maximum displacement or acceleration amplitude decreases, and the response peaks shift to the direction of low KC number. After applying the end pretension, the horizontal displacement and acceleration amplitude of the tube decrease, but the vertical displacement and acceleration amplitude increase. Increasing the end pretension will increase the mooring tension, and the tension amplitude of the waveward side is always higher than that of the leeward side.

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Fig. 2. Overall and detailed model photos.

How NOKOV Contributes to the Research

The movement measurement system is the NOKOV non-contact multi-eye measurement system (ver. 2020) produced by Beijing NOKOV Science& Technology Co., Ltd. The system consists of 24 cameras and 15 light marks connected to the model tube through a steel frame. 24 cameras located on both sides of the basin take continuous photos of the marked points and calculate the co-ordinates of each measuring point through image analysis.

Citation Yang Z, Wang Z, Fu S, et al. Experimental study on 3D hydroelastic response of entire long span submerged floating tunnel with catenary-mooring constraint and perpendicular regular waves action[J]. Tunnelling and Underground Space Technology, 2025, 155: 106181.

Link https://www.sciencedirect.com/science/article/pii/S0886779824005996

Experimental study on dynamic responses of a new semi-submersible supporting platform concept for 10 MW wind turbines

Keywords

Novel semi-submersible supporting platform, Floating wind turbine, Dynamic response, Model test, Experimental analysis

Abstract

An irreplaceable model test has been conducted to analyze the dynamic behaviors featured with multidisciplinary properties for a novel semi-submersible platform (named as New Semi) to support the DTU 10 MW reference wind turbine (RWT) by using 1/75 scale model wave tank test result. The thrust performance-matched rotor in low-Reynolds numbers is used to address the Froude-Reynolds scaling conflict, and the generator variable speed and independent blade-pitch control system for the 10 MW model FOWT system is innovatively designed. After calibrating the thrust performance-matched model rotor, the dynamic performance-matched model mooring system and the model platform at Froude-scaled periods, the model tests are performed using realistic marine environmental parameters. In the static and regular wave test, the test data certifies that the model system mass and the mooring restoring stiffness are quite correct. In the combined wind and waves test, the motions responses and structural dynamics are examined under specific operational and extreme conditions, the motions responses of the New Semi concept are mainly dominated by the low frequency (LF) parts in all load cases, except the heave in extreme sea sate, and the statistics of the experimental campaigns also further proves the performance reliability assessed by DNV standards.

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Fig. 8. Configuration of rotor model and assembled wind turbine model.

How NOKOV Contributes to the Research

The 6DoFs rigid-body motions of the New Semi concept is captured by a non-contact Nokovpassiveopticaltrackingsystem, and the four passive Marker points are placed on the New Semi platform and the nacelle, as shown in Figs. 6 and 8. The wave gauges and a hot-wire anemometer are used to capture the wave heights and inflow wind speeds, respectively. Furthermore, the detailed type and range of various sensors can be listed in Table 7.

Citation Zhao Z, Chang S, Li X, et al. Experimental study on dynamic responses of a new semi-submersible supporting platform concept for 10 MW wind turbines[J]. Ocean Engineering, 2025, 318: 120168.

Link https://www.sciencedirect.com/science/article/abs/pii/S0029801824035066

Frogman Self-Navigation Method Based on Virtual Transponder Array and Dead Reckoning

Keywords

Frogman self-navigation, integrated navigation, single transponder, underwater acoustic positioning, virtual transponder array.

Abstract

Using single transponder ranging (STR) information to aid positioning satisfies the needs of frogman autonomous positioning in waters emergency rescue, where miniaturized and low-cost devices are preferred. On this basis, a frogman self-navigation method based on virtual transponder array (VTA) and dead reckoning (DR) is proposed in this article, to solve the problem that calculation results of DR still accumulate with time when STR information is taken as the external measurement. In the proposed method, firstly, by constructing the VTA with depth information constraint, frogman autonomous positioning under the condition of single transponder confi-guration is realized. Then, to combine the characteristics that DR positioning data is smooth and short-term stable, and that VTA positioning error is not cumulative, the DR navigation system is used to describe frogman's motion law, the frogman positioning coordinates that calculated by VTA are taken as external measurement and the Kalman filter is designed, which solves the problem of DR accumulated errors. Compared to traditional STR-DR method, the proposed VTA-DR method further improves the accuracy and stability of frogman navigation and positioning. Finally, based on the high-precision three-dimensional motion capture system, the semi-physical simulation experimental environment is built to verify the proposed method. The experimental results under different tracks indicate that the average total location error of VTA-DR method is 0.149m, which is reduced by 53.5% compared with STR-DR method. The proposed VTA-DR method can better suppress the accumulation of positioning errors and has better positioning accuracy and robustness.

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FIGURE 6. Nokov 3D Optical motion capture system.

How NOKOV Contributes to the Research

A. EXPERIMENTAL EQUIPMENT AND SCHEME
1) EXPERIMENTALEQUIPMENT
2) Nokov 3DOpticalmotioncapture systemNokov 3D optical motion capture system can capture and output the accurate three-dimensional data of the object to be measured, which is mainly composed of infrared optical motion capture lens, operation, analysis and processing software and related accessories. The accuracy of system can reach sub-millimeter level, which meets the requirements of evaluating the positioning accuracy of the method we have proposed in this article. The Nokov 3D optical motion capture system is shown in Fig. 6. It is used as the recorder of experimenter's movement parameter, and the high-precision position, velocity and attitude information output by motion capture system will be the evaluation benchmark of the navigation results. In addition, part of the data will be processed to simulate the truth value of the output signals of underwater navigation subsystems such as DVL and single transponder acoustic ranging system. The specific simulation scheme will be described in detail in the next part of this section.

Citation Zhang Y, Wang N, Li M, et al. Frogman self-navigation method based on virtual transponder array and dead reckoning[J]. IEEE Access, 2020, 8: 177329-177340.

Link https://ieeexplore.ieee.org/abstract/document/9207928

Identification of ice loads on offshore wind turbines in cold regions using RBFNN-GA

Abstract

Accurate identification of ice loads is crucial for ensuring the structural safety and service life of offshore wind turbines (OWTs) operating in cold regions. Although full-scale measurements are considered the most reliable method for obtaining ice loads, their long-term application is limited by high costs, harsh environmental conditions, and the complexity of ice-structure interactions. To address this challenge, this study proposes a hybrid machine learning method that combines a radial basis function neural network (RBFNN) with a genetic algorithm (GA) to identify ice loads based on structural dimensions and environmental parameters. High-fidelity data are first compiled from full-scale measurements, physical model tests, and numerical simulations. Input features are then selected through empirical analysis and correlation evaluation. Based on this, an RBFNN model is developed, with its architecture and parameters globally optimized using a GA. To verify the model's accuracy and engineering applicability, ice-structure collision experiments are performed in a wave flume, and the predicted results are compared with the measured data. The results indicate that pile diameter, ice thickness, and ice drift velocity are key input features influencing the model's prediction performance. Optimization using the GA significantly improved both accuracy and generalization, reducing the average error by about 28% compared to the traditional RBFNN model. The method proposed in this paper provides an efficient and scalable solution for the inverse identification of ice loads on OWTs in cold regions, addressing the accuracy and stability limitations of traditional inversion techniques.

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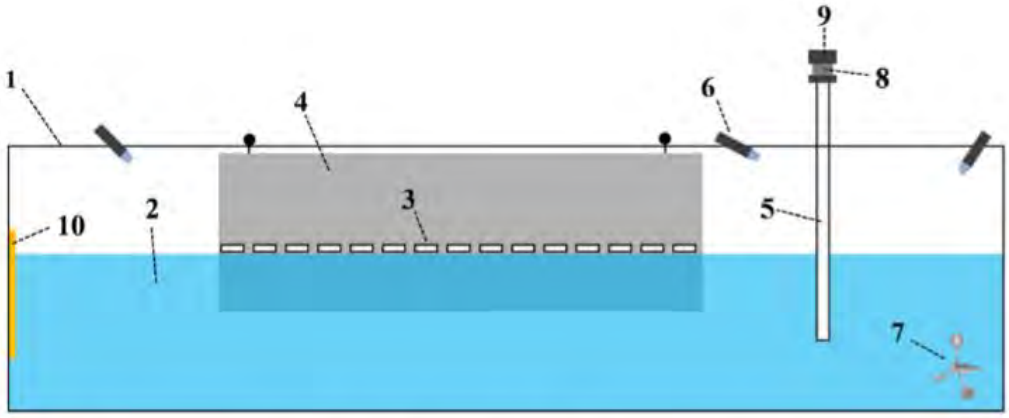

FIG. 5. Schematic of the wave flume and its associated equipment: 1—wave flume; 2—water; 3—model ice; 4—anti-drift net; 5—cylindrical riser; 6—dynamic motion capture cameras; 7—velocimeter; 8—force sensor; 9—fixture; 10—wave generator.

How NOKOV Contributes to the Research

To further evaluate the applicability and accuracy of the RBFNN-GA model proposed in this study for practical applications, the ice load test on cylindrical structures at China University of Petroleum's Wave Flume (CUPWF) is introduced. The wave flume measures 40 m in length, 1.2 m in width, and 2.5 m in height. It is equipped with a YTCL3005L micro-force sensor, an LSH10-1S ultrasonic Doppler velocimeter, NOKOV dynamic motion capture cameras, sensor mounting fixtures, and an anti-drift net, among other auxiliary devices. Figure 5 illustrates a schematic of the wave flume and its associated equipment. In this experiment, a cylindrical vertical pipe is used to simulate the foundation pile of wind turbines, with a model diameter of 0.1 m and a scale ratio of 1:20. The preparation of sea ice is a critical aspect of collision experiments between ice and cylindrical risers. In this study, non-freezing paraffin model ice is used to simulate natural sea ice.

Citation Zhou C, Chen L, Liu W, et al. Identification of ice loads on offshore wind turbines in cold regions using RBFNN-GA[J]. AIP Advances, 2025, 15(11).

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001615908200001

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Leg Mechanism Design and Motion Performance Analysis for an Amphibious Crab-like Robot

Keywords

amphibious environment, bionic, parallel leg mechanism, multi-legged robot, motion performance analysis

Abstract

Bionic-legged robots draw inspiration from animal locomotion methods and structures, demonstrating the potential to traverse irregular and unstructured environments. The ability of Portunus trituberculatus (Portunus) to run flexibly and quickly in amphibious environments inspires the design of systems and locomotion methods for amphibious robots. This research describes an amphibious crab-like robot based on Portunus and designs a parallel leg mechanism for the robot based on biological observations. The research creates the group and sequential gait commonly used in multiped robots combined with the form of the robot' s leg mechanism arrangement. This research designed the parallel leg mechanism and modeled its dynamics. Utilizing the outcomes of the dynamics modeling, we calculate the force and torque exerted on each joint of the leg mechanism during group gait and sequential gait when the robot is moving with a load. This analysis aims to assess the performance of the robot's motion. Finally, a series of performance evaluation experiments are conducted on land and underwater, which show that the amphibious crab-like robot has good walking performance. The crab-like robot can perform forward, backward, left, and right walking well using group and sequential gaits. Simultaneously, the crab-like robot showcases faster movement in group gaits and a more substantial load capacity in sequential gaits.

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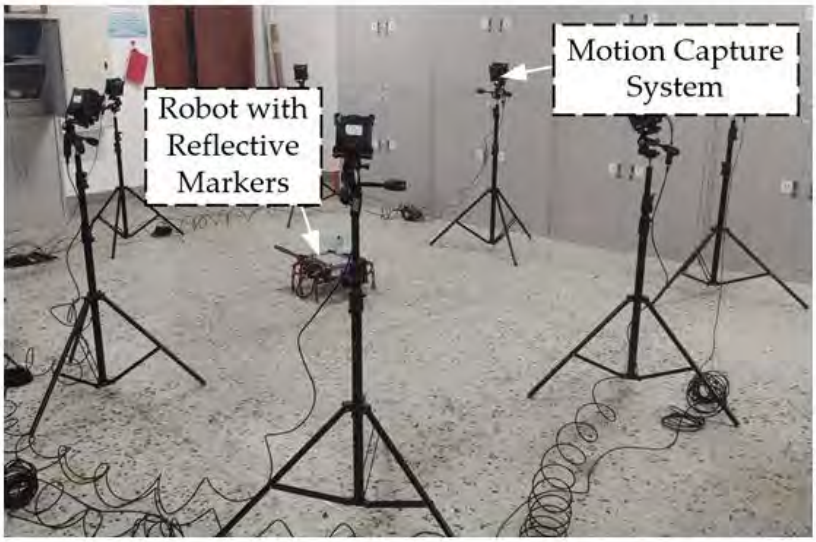

Figure 16. An overview of the robot motion experiment.

How NOKOV Contributes to the Research

We build an experiment platform for robot walking experiments. Figure 16 shows a schematic diagram of the experimental platform for the crab-like robot, including the motion capture system (NOKOV MARS 2H) and the crab-like robot prototype in two parts. Motion commands are sent to the robot by radio, and the motion capture system captures the robot's movement in real instances.Videos S2 and S3 of the Supplementary Material shows the robot's land walking process, including the robot moving forward, walking left, walking right and turning in place.

Citation Hu S, Ma X, Chen X, et al. Leg Mechanism Design and Motion Performance Analysis for an Amphibious Crab-like Robot[J]. Journal of Marine Science and Engineering, 2023, 12(1): 10.

Link https://www.mdpi.com/2077-1312/12/1/10

Manta Ray-Inspired Soft Robotic Swimmer for High-speed and Multi-modal Swimming

Abstract

Manta rays exhibit complex motion behavior through their flexible fins. This study proposes a novel manta ray-inspired soft robotic swimmer with bistable flapping wings for high-speed and multi-modal swimming. The wings are created with prestressed bistable composite and actuated by small McKibben artificial muscles. Pressurizing and depressurizing the McKibben actuators integrated into the flapping wings generates alternating snap-throughs between two stable states, yielding swimming. Experiments are set up and conducted to analyze how the robot responses vary as a function of input pressures and actuation frequencies for both bistable and monostable modes. Experimental results show that the highest swimming velocity is 0.58 body lengths (BL) per second (equivalent to 12.23 cm/s), and the maximum turning angle speed is 22.5° per second with a smaller turning radius by holding the fins in asymmetric positions for bistable modes. Multimodal swimming motions are achieved including forward and backward translating, turning, and flip-turning.

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How NOKOV Contributes to the Research

To quantify swimming speed, the robot is directed to perform ten cycles of PWM square wave motions under different pressures. Velocity is subsequently recorded by a NOKOV motion capture system.

Citation Xu Z, Liang J, Zhou Y. Manta Ray-Inspired Soft Robotic Swimmer for High-speed and Multi-modal Swimming[C]//2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2024: 235-240.

Link https://ieeexplore.ieee.org/document/10802678

Model Predictive Control for an Autonomous Underwater Robot with Fully Vectored Propulsion

Abstract

Due to the low motion efficiency and maneuver-ability of underwater robots with six degrees of freedom, it is challenging for them to respond quickly to the attitude requirements during underwater autonomous manipulation. This paper presents a novel autonomous underwater robot with fully vectored propulsion and a model predictive control method to achieve more agile and efficient movements autonomously. In detail, we first design a robot with eight vector-distributed thruster layouts for fully vectored propulsion and construct the software architecture based on the robot operating system (ROS). Then, we establish the hydrodynamic model by adopting the Fossen approach and construct a 13-dimensional system state-space equation, which is discretized using the explicit fourth-order Runge-Kutta method. To achieve autonomous manipulation, model predictive control is employed along with physical constraints of the custom-built robot to enable real-time prediction and optimization of the robot's states for control purposes. Finally, numerical simulations and experiments of the Point-to-Point Motion are conducted to test the robot's performance. Experimental results reveal that the average error of each direction is 0.0027 m, 0.0031 m, and 0.0368 m in the x-axis, y-axis, and z-axis, respectively, and 0.8502°, 2.1941°, 0.2408° corresponding to three attitude angles, which verify the performance of employing MPC to control an autonomous underwater robot with fully vectored propulsion.

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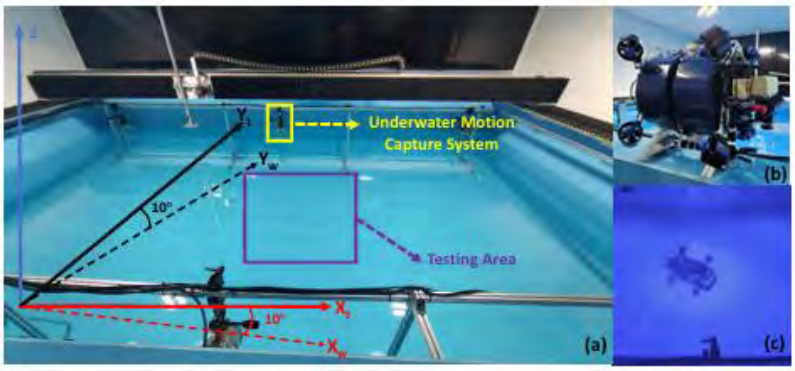

How NOKOV Contributes to the Research

The experiment was conducted in a 5 m × 3 m × 1.5 m indoor rectangular tank, surrounded by a set of NOKOV Motion Capture System with six underwater cameras, and the sampling rate of the system is 100 Hz.

Citation T. Gao et al., "Model Predictive Control for an Autonomous Underwater Robot with Fully Vectored Propulsion," 2024 IEEE International Conference on Robotics and Automation (ICRA), Yokohama, Japan, 2024, pp. 10482-10488, doi: 10.1109/ICRA57147.2024.10611025.

Link https://ieeexplore.ieee.org/document/10611025

Modeling and Oscillation Suppression for a Rigid-flexible Coupled Tail in a Crocodile-inspired Robot During Terrestrial Locomotion

Keywords

Rigid-flexible coupling structure · Crocodile-inspired robot tail · Underactuated oscillation suppression · Nonlinear model predictive control (NMPC) · Dynamic modeling

Abstract

Inspired by the crucial role of the tail in crocodile locomotion, we propose a novel rigid-flexible coupled tail structure design. The tail design reduces the number of required actuators, enables undulatory propulsion in swimming, and provides additional support during terrestrial crawling. However, when the tail lifts off the ground during land crawling, its flexible underactuated structure tends to oscillate randomly due to minimal damping. These oscillations impart disruptive reaction torques to the body, critically impairing locomotion stability. To tackle this issue, we employed the standard Denavit-Hartenberg (DH) method and Newton-Euler equations to formulate a rigid-flexible coupled dynamic model for the tail, in which distributed elastic forces are embedded as internal forces in the force balance equations. Based on this model, we propose an oscillation suppression strategy based on an energy-optimized Nonlinear Model Predictive Controller (NMPC) with a single joint torque as the control input. This controller solves a constrained multi-objective optimization problem to effectively suppress the underactuated oscillations of the tail. Finally, experimental comparisons validate the accuracy of the dynamic model, and simulations based on this model substantiate the effectiveness of the oscillation suppression strategy.

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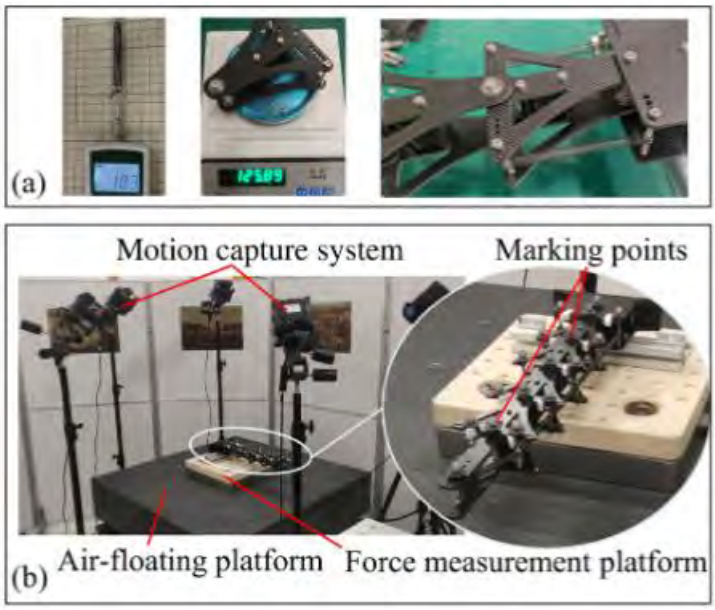

Fig. 6 Dynamic testing of the tail test platform. **a** Parameter measurement calibration and structure assembly. **b** Robotic tail test platform

How NOKOV Contributes to the Research

As shown in Fig. 6b, a KISTLER Micro-Vibration Ceramic Dynamometer (type:9236A2, Switzerland) is used to measure forces and calculate moments on the base at 2 kHz, and a NOKOV motion capture system (type: MARS 4H, Beijing, China) is used to track the movement trajectory of the link at 2 kHz. The force measurement platform is installed on a marble air-floating vibration isolation plat-form to minimize external interference. Six motion capture cameras are placed at different heights around the force plat-form. The root of the tail is fixed on the force platform, and 12 mm marking points are attached to the four joint origins and the end of the tail point (marking points: P1-P5) to track the motion during oscillation.

Citation Zhuo Z, Jia W, Fang M, et al. Modeling and Oscillation Suppression for a Rigid-flexible Coupled Tail in a Crocodile-inspired Robot During Terrestrial Locomotion[J]. Journal of Bionic Engineering, 2025: 1-15.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001596881200001

Multi-dynamic target coverage tracking control strategy based on multi-UAV collaboration

Keywords

Coverage control, Multi-dynamic targets, Multi-UAV, Tracking control, Marine oil spills

Abstract

In response to the issues of mutual interference among multiple targets, dynamic changes in coverage area, and the difficulty in accurately estimating the optimal coverage positions during the coverage and tracking control process, this article proposes a multi-dynamic target coverage tracking control strategy based on Multiple Unmanned Aerial Vehicle (Multi-UAV) cooperation. To address the problem of estimating the number and location of optimal coverage points for multi-dynamic targets, we propose a dynamic estimation strategy of optimal coverage points for multi-dynamic targets; for the under-coverage problem, we propose an optimal coverage point estimation method for under-coverage conditions in order to improve the cost-effectiveness of coverage. Subsequently, a multi-UAV scheduling strategy based on the coverage cleanup cost is proposed, which assigns appropriate UAVs to perform coverage cleanup tasks for different coverage points. Addressing the performance constraints, path smoothness, collision avoidance, and path tracking problems of UAVs, we introduce B-spline-based multi-UAV path planning and line-of-sight-based guidance methods to achieve multi-UAV coverage tracking control for multi-dynamic targets. Finally, the proposed method is applied to an ocean oil spill coverage cleanup task. Both simulation and emulation results validate the theoretical findings and demonstrate the effectiveness of the proposed method for such applications.

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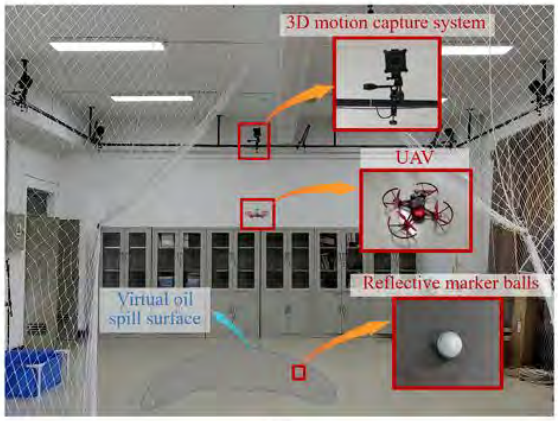
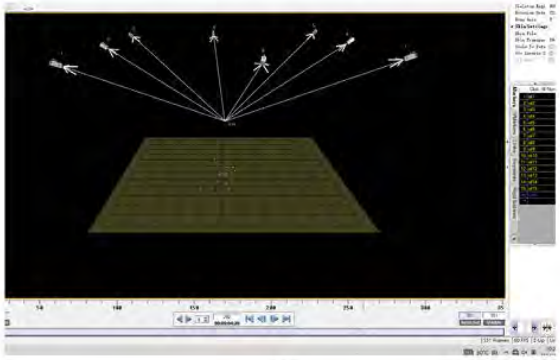


(a)



(b)

Fig. 19. Dynamic target coverage tracking control experiment in laboratory environment. (a) Coverage tracking experimental platform. (b) Measurement data of 3D motion capture system.

How NOKOV Contributes to the Research

To validate the practical application capabilities of the proposed algorithm, we completed a multi-UAV cooperative multi-dynamic tar get coverage tracking control based on the existing equipment in our laboratory, as shown in Fig. 19. We regard fluorescent marker balls as oil particle points, throwing multiple marker balls close to the ground to simulate the drift and spreading of the oil spill surface. Additionally, we utilized a 3D motion capture system to locate and track the oil particle points.

Citation Sun Q, Liu W, Cai L. Multi-dynamic target coverage tracking control strategy based on multi-UAV collaboration[J]. Control Engineering Practice, 2025, 155: 106170.

Link https://www.sciencedirect.com/science/article/abs/pii/S0967066124003290

NDO-SMC for trajectory tracking of AUVs with unmeasured states: experimental study

Keywords

autonomous underwater vehicle, disturbance observer, velocity-free, sliding mode control

Abstract

This paper focuses on the three-dimensional trajectory tracking of autonomous underwater vehicles (AUVs) and proposes a nonlinear disturbance observer-based sliding mode control (NDO-SMC) scheme that operates without linear velocity and acceleration measurements. First, a four-degree-of-freedom AUV model accounting for uncertainties and external disturbances is established. Then, to tackle the issue of unmeasurable linear velocity, a second-order differentiator is proposed for velocity estimation, which guarantees bounded velocity estimation errors. Next, an NDO-SMC scheme is developed that eliminates the requirement for linear velocity and acceleration feedback, with theoretical analysis verifying bounded trajectory tracking errors under uncertainties and external disturbances. Finally, comprehensive simulations and experiments are conducted to validate the proposed method, confirming its strong robustness across multiple scenarios.

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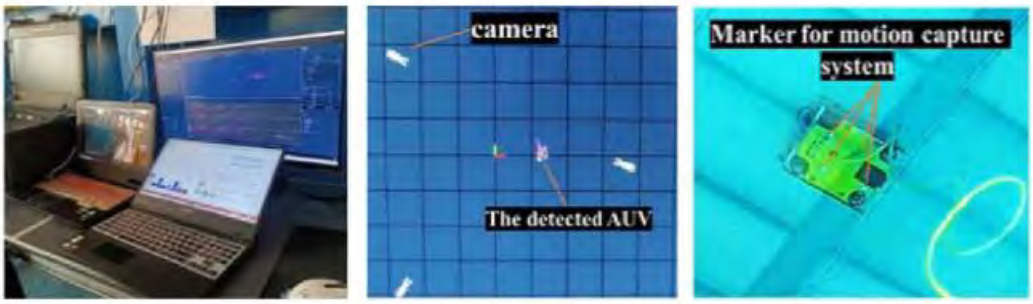

Figure 6. The upper computer, motion capture system and makers.

How NOKOV Contributes to the Research

The AUV is controlled via a laptop (i5-8300 H, 16 GB RAM) with a C# programmed controller.The laptop sends the desired force/torque to an STM32 H723 for thruster control. Horizontal positionis measured by a NOKOV motion capture system (figure6), depth by a depth sensor, and attitude by aSINS; a DVL is equipped for differentiator comparison. Sampling time is 100 ms.

Citation Chen H, Ye Z, Tang G, et al. NDO-SMC for trajectory tracking of AUVs with unmeasured states: experimental study[J]. Measurement Science and Technology, 2025, 37(2): 026201.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001651350900001

Optimization of pendulum-based wave energy converter through mathematical approximation

Keywords

Wave energy, Parametric pendulum, Perturbation technique, Mathematical approximation, Multiple degrees of freedom

Abstract

This study analyzes a pendulum-based wave energy converter with multiple degrees of freedom and a rigid hull encapsulation design that enhances robustness and extends lifespan. The kinetic equation of the vertical axis parametric pendulum is proposed alongside the concept of the Prescribed Excitation Model. This model can be applied to evaluate the pendulum's performance in the early design stage at an extremely low cost. A mathematical approximation of this model is derived using the Perturbation Technique. The maximum linear damping obtained from the approximation provides a reference value for the numerical model, reducing the simulation quantity required for optimization. The power assessment of the pendulum through both mathematical approximation and numerical simulation is compared, indicating that the mathematical approximation is reliable for comparing the performance of different pendulums. Finally, a case study reveals that mounting the pendulum upon the mass center of the hull enhances performance. Additionally, the mass of the pendulum and its moment of inertia have less influence on the optimization of the mounting position, suggesting that the optimization process can be divided into two separate parts. The numerical modeling shows that the pendulum under optimal mounting position has the potential to product energy of 6.79 MW·h (annually).

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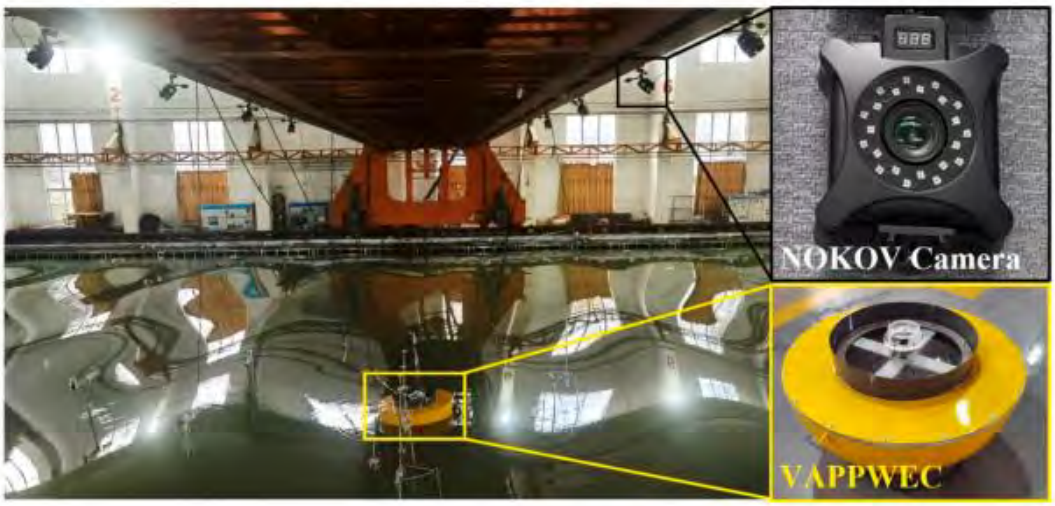

Fig. 10. Experiment campaign.

How NOKOV Contributes to the Research

An experiment campaign is carried out to analyze the hull's reso-nance characteristics, as shown in Fig. 10. The physical properties of the hull and the corresponding mooring system are listed in Table 2 andTable 3. The spread mooring system consists of four catenary lines, theangles between the mooring lines and the incident wave are 45 ,135 ° , 225 °,and 315 °,respectively. The response of hull is measured by NOKOV Motion Capture System. Fig. 11 demonstrates the simulationresults of WEC-Sim as well as the comparison with model test, in waveheight of 10 cm.

Citation Jiang X, Cao F, Shi H, et al. Optimization of pendulum-based wave energy converter through mathematical approximation[J]. Applied Energy, 2025, 378: 124754.

Link https://www.sciencedirect.com/science/article/abs/pii/S0306261924021378

Passivity-based variable damped sliding mode control for cable-driven wave motion compensation device under hybrid disturbances

Keywords

Wave motion compensation, Port-Hamiltonian system, Fast terminal sliding mode, Damping modulation, Cascaded observer

Abstract

Cable-driven wave motion compensation devices are essential for safe maritime operations, including offshore supply missions and marine engineering tasks. In suspended cable configurations, the dynamic performance is inherently constrained by payload weight, since gravity not only enables force closure but also limits the available control authority. Moreover, the system is constantly subjected to wave-induced disturbances, which exacerbate platform oscillations and further challenge controller robustness. To tackle these issues, a novel passivity-based control approach is proposed in this paper that integrates fast terminal sliding mode control with adaptive damping modulation.

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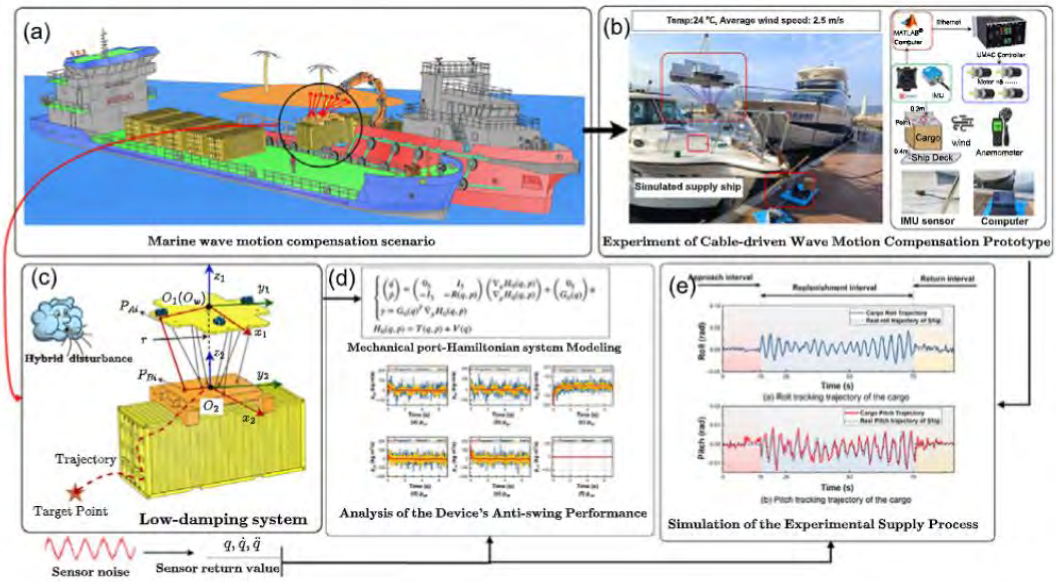

How NOKOV Contributes to the Research

The experimental platform is composed of three key components. The first component is an octo-cable driven system equipped with actuators featuring a 10:1 gear ratio. The second component involves a 6-DOF Stewart platform specifically designed to emulate realistic deck motions. The third component integrates a UMAC motion controller that establishes communication with an IMU sensor and a NOKOV motion capture system through MATLAB/Simulink, operating at a 10 Hz sampling frequency to ensure real-time pose feedback synchronization. This configuration combines mechanical actuation, dynamic motion simulation, and closed-loop control capabilities into a cohesive experimental setup. Wind disturbances are generated by a three-stage blower and measured by an anemometer. The motion capture system provides the actual coordinate trajectories of the markers. Through the sensors, experimental data are acquired in real time for subsequent analysis. Since the cargo is rigid, the desired trajectory of its center can be derived through a simple coordinate transformation. The control architecture is implemented by compiled UMAC programs to ensure real-time deterministic execution. Hardware architecture supports the acquisition of various data required in the experiment. Fig. 18a details the anti-swing trajectory combining 2-axis translation, y-axis displacement, and x-axis rotation to emulate characteristic vessel swing and roll motions.

Citation Hou, Zongbin, Ruihao Sui, and Yuan Chen. "Passivity-based variable damped sliding mode control for cable-driven wave motion compensation device under hybrid disturbances." Information Sciences (2025): 122742.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001599105100004

Proprioceptive State Estimation for Amphibious Tactile Sensing

Abstract

This paper presents a novel vision-based proprio ception approach for a soft robotic finger that can estimate and reconstruct tactile interactions in terrestrial and aquatic environments. The key to this system lies in the finger's unique metamaterial structure, which facilitates omni-directional passive adaptation during grasping, protecting delicate objects across diverse scenarios. A compact in-finger camera captures high framerate images of the finger's deformation during contact, extracting crucial tactile data in real time. We present a volu metric discretized model of the soft finger and use the geometry constraints captured by the camera to find the optimal estimation of the deformed shape. The approach is benchmarked using a motion capture system with sparse markers and a haptic device with dense measurements. Both results show state-of the-art accuracies, with a median error of 1.96 mm for overall body deformation, corresponding to 2.1% of the finger's length. More importantly, the state estimation is robust in both on-land and underwater environments as we demonstrate its usage for underwater object shape sensing. This combination of passive adaptation and real-time tactile sensing paves the way for amphibious robotic grasping applications.

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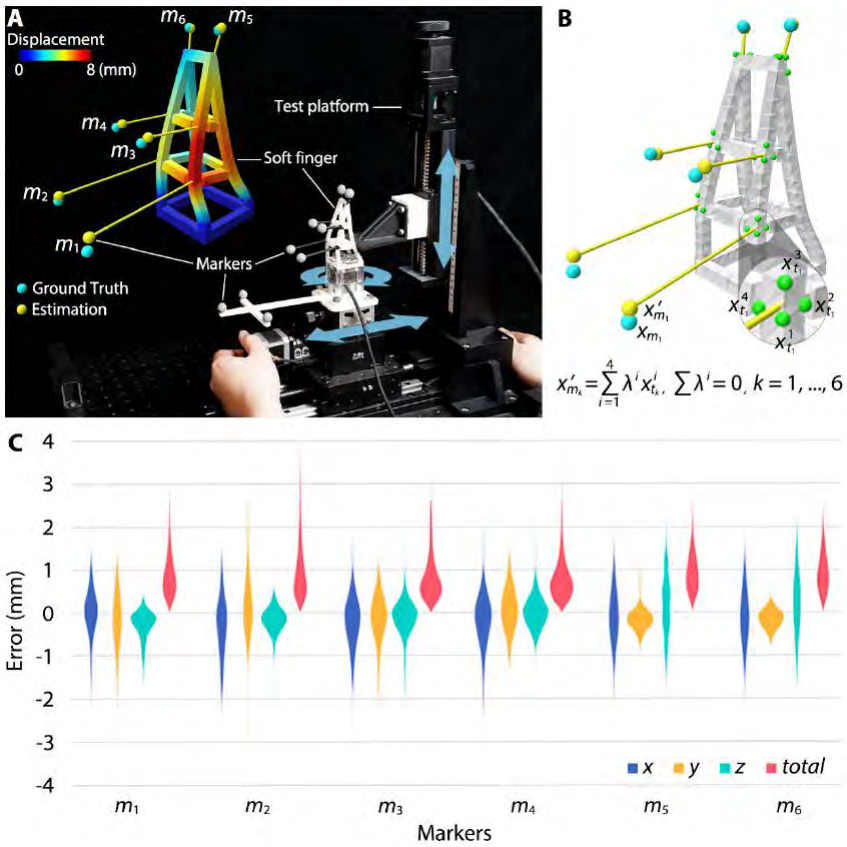

How NOKOV Contributes to the Research

A motion capture system (Mars2H by Nokov, Inc.) was used to track finger deformations through nine markers with an 8 mm radius. Among them, six markers were divided into three pairs, which were rigidly attached to the fingertip (m5,m6), the first layer (m3,m4), and the second layer (m1,m2) of the soft finger, respectively. The other three markers were attached to the platform and used as the reference reading to align the motion capture system's reference frame with the platform's coordinate frame.

Citation N. Guo et al., "Proprioceptive State Estimation for Amphibious Tactile Sensing," in IEEE Transactions on Robotics, vol. 40, pp. 4684-4698, 2024, doi: 10.1109/TRO.2024.3463509.

Link https://ieeexplore.ieee.org/document/10684118

Real-time hybrid model experimental and numerical study of a novel 15 MW semi-submersible wind turbine

Keywords

Floating offshore wind turbine, Real-time hybrid model, Wave basin tests, Numerical simulation, Software-in-the-loop, Offshore wind energy

Abstract

Physical model testing is essential for advancing the development of floating offshore wind turbines (FOWTs), as it supports both the understanding of their dynamic performance and the validation of numerical simulation tools. A key challenge lies in the scaling conflict between hydrodynamic and aerodynamic forces, governed by the Froude and Reynolds similarity laws, respectively. This conflict limits the fidelity of conventional wind tunnel and wave basin tests. To address this issue, this study proposes a real-time hybrid model (RTHM) testing method that physically and numerically models the aerodynamic and hydrodynamic subsystems. Compared to previous approaches, this method broadens the range of load reproduction, reduces errors, and improves response speed by integrating a seven-propeller actuator, coupling an advanced aerodynamic analysis tool, and developing a robust command loop. A scaled RTHM of a 15 MW FOWT is constructed and tested under steady wind, turbulent wind, and combined wind-wave conditions. The aerodynamic load reproduction performance of the proposed method is thoroughly evaluated, and the coupled effects of aerodynamic and hydrodynamic loads on FOWT motion responses are systematically analysed. Results show that the actuator achieves a thrust variation rate of up to 266 kN·s\\(^{-1}\\) and accurately reproduces the aerodynamic thrust, torque, and moments at the rotor centre with a 40 ms loop cycle. Reproduction accuracy of thrust and torque remains above 96 % near the rated wind speed, and repeatability exceeds 95 %. Wave conditions have negligible impact on aerodynamic load fidelity. Motion responses from the RTHM agree well with fully coupled numerical predictions, except near the natural frequencies of platform surge and pitch. The proposed method offers a reliable, scalable, and cost-effective solution for high-fidelity experimental investigations of FOWTs.

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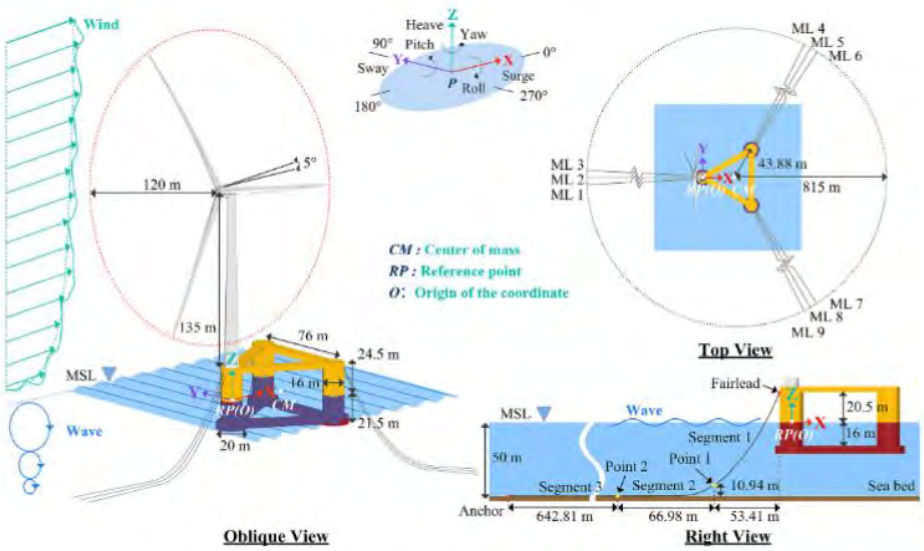

Fig. 1. Conceptual diagram of a novel 15 MW FOWT.

How NOKOV Contributes to the Research

Before testing, the plane coordinates of the origin, anchor, model initial position, and wave height sensors were determined using a PENTAX Total Station. A pendulum-based moment of inertia measurement rig is employed to calibrate the centre of mass and mass moment of inertia of the scaled model, with a HWT9073-CAN nine-axis attitude sensor providing precise measurements of the oscillation angles. During testing, an SRI-3815D six-axis load cell, installed at the top of the tower, is used to measure aerodynamic loads. Load cells are placed between each mooring line and the fairlead to measure mooring line tension. An array of TKS-7-BG capacitive wave height gauges is positioned around the model to monitor wave height. The displacement and acceleration of the scaled model in the wave basin are tracked using the NOKOV optical motion capture system, which consists of eight MARS9H cameras, a switch, and real-time processing software (XINGYING 3.0) [65]. This system provides localization accuracy better than 0.1 mm, with a time delay of less than 3 ms. The NOKOV system supports real-time data sharing with tools such as MATLAB, Python, and LabVIEW through its Software Development Kit (SDK). The system, along with other sensors, operates at a sampling frequency of 200 Hz. Data synchronization between the NOKOV system and the DAQ is achieved via a synchronized signal generator. The DAQ incorporates a built-in low-pass filter matched to the sensor bandwidth, which attenuates high-frequency noise beyond the usable range.

Citation Han M, Cao F, Shi H, et al. Real-time hybrid model experimental and numerical study of a novel 15 MW semi-submersible wind turbine[J]. Energy Conversion and Management, 2025, 346: 120463.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001569066300001

Real-Time Millimeter-Accurate Underwater Pose Estimation via Tightly-Coupled Fusion of Vision and Optical Tracking

Keywords

Underwater robotics, sensor fusion, pose estimation, optical tracking, visual odometry

Abstract

Precise and high-frequency state estimation is required for advanced underwater robotic applications such as physical interaction and agile control, yet no single sensor can simultaneously provide both high accuracy and high update rates. Vision-based methods offer high-frequency updates but suffer from drift, while optical tracking systems are highly accurate but may not provide sufficiently high update rates for real-time control loops. This letter presents a tightly-coupled sensor fusion framework that combines a high-frequency (62 FPS) monocular vision-based pose estimator with a high-accuracy (millimeter-level) optical tracking system. Our approach uses a visual estimator for high-frequency state propagation—with a latent variable motion model to compensate for underwater disturbances—while the optical tracker provides periodic corrections. In a controlled underwater testbed, this achieves a position RMSE of 5.65 mm at 62 FPS, improving accuracy 1.6 × compared to the best baseline method (EfficientPose + EKF: 9.20 mm) and 6.4 × compared to vision-only estimation (36 mm). Our dataset and code are available upon request.

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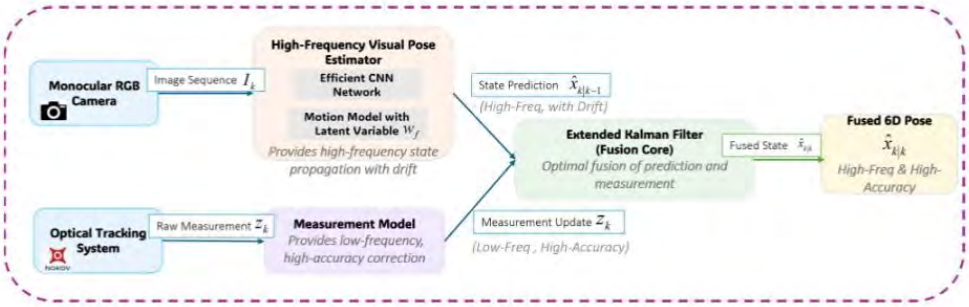

Fig. 1. An overview of our proposed real-time sensor fusion framework. The system integrates two complementary data streams: a high-frequency visual pose estimator provides state predictions, while a high-accuracy optical tracking system provides measurement updates. An EKF serves as the fusion core, combining these streams to produce a final state estimate that is both high-frequency and high-accuracy.

How NOKOV Contributes to the Research

To address this trade-off, this letter proposes the real-time fusion of complementary sensor modalities. The proposed approach integrates two systems: (i) a high-frequency (62 FPS) monocular vision pose estimator that tracks known markers on the robot, and (ii) a high-accuracy (±0.5 mm) commercial optical tracking system (NOKOV) that provides precise position measurements at lower frequencies. In this framework, the vision system handles prediction while the optical tracker provides corrective updates, creating a fusion loop that maintains both speed and accuracy.

Citation Gao Y, Xu T, Cai Y. Real-Time Millimeter-Accurate Underwater Pose Estimation via Tightly-Coupled Fusion of Vision and Optical Tracking[J]. IEEE Robotics and Automation Letters, 2025, 11(2): 1218-1225.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001638044400014

Robust hybrid visual servoing for hovering control of autonomous underwater vehicles in unstructured environments

Keywords

Autonomous underwater vehicles, Hybrid visual servoing, Hovering control, Robust H∞ contro, Unstructured environments

Abstract

This paper presents a novel hovering control method for autonomous underwater vehicles (AUVs) based on a hybrid visual servoing (HVS) framework, designed to achieve accurate and stable pose regulation of AUVs relative to static targets in unstructured underwater environments. The proposed method, which integrates a robust \\(H_\infty \\) controller within a dual-loop control architecture, effectively addresses underwater image degradation, parameter uncertainties, and external disturbances encountered in unstructured environments. In the outer loop, visual features derived from image moments of underwater targets are utilized to design a position control law, enhancing robustness against underwater image degradation. In the inner loop, a robust \\(H_\infty \\) controller is designed to accurately track the velocity commands generated by the outer loop, providing robustness against hydrodynamic coefficient perturbations and external disturbances. The performance of the proposed hovering control method is validated through extensive comparative simulations and experiments using an AUV prototype. Results demonstrate that the method enables accurate and stable hovering control of the AUV, supporting autonomous close-range observation of underwater targets in unstructured environments.

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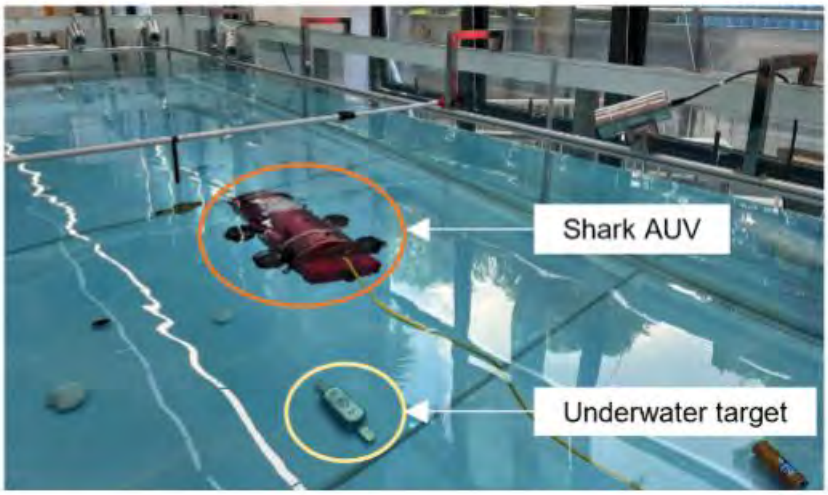

Fig. 17. Laboratory pool with a motion capture system, a sacrificial anode is used as the target for observation and placed at the bottom of the pool.

How NOKOV Contributes to the Research

5\. Experimental validations
5.1. Experimental platform
To further evaluate the performance of the proposed hovering control method, a series of experiments were conducted using an AUV prototype (see Fig. 16) in a controlled laboratory pool. The technical parameters of the AUV prototype are summarized in Table 3. The mechanical structure of the AUV is symmetric with respect to the xoz and xoy planes and approximately symmetric about the yoz plane. This geometric configuration enables the decoupling of motions in the heave, roll, and pitch DoFs (Fossen, 2011). Additionally, the AUV is designed with metacentric restoring forces, which facilitate passive stabilization in the pitch and roll DoFs. The experiments were conducted in a laboratory pool measuring 3 × 6 × 1.6 m (L × W × H), as shown in Fig. 17. The AUV was equipped with a downward-looking camera for target perception, and its Euler angles were recorded by the onboard IMU (Vit Motion). A motion capture system (NOKOV) was employed to track the AUV's pose and velocities. A sacrificial anode, which is commonly encountered in underwater pipeline and ship hull inspection tasks, was selected as the observation target and placed at the bottom of the pool.

Citation Hong L, Wang X, Zhang D. Robust hybrid visual servoing for hovering control of autonomous underwater vehicles in unstructured environments[J]. Ocean Engineering, 2025, 339: 122103.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001529778600002

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ROV6D: 6D Pose Estimation Benchmark Dataset for Underwater Remotely Operated Vehicles

Keywords

6D Pose Estimation Dataset, Underwater Remotely Operated Vehicles, Underwater Neural Rendering, Motion Capture System, Visual Perception.

Abstract

Accurately localization between multi-robots is crucial for many underwater applications, such as tracking, convoying and subsea intervention tasks. 6D pose estimation is a fundamental task that enables precise object localization in 3D space with full six degrees of freedom. However, one critical challenge is the lack of available large-scale datasets due to the unbearable cost of labelled data collection. To overcome this difficulty, we propose a benchmark dataset, ROV6D, for 6D pose estimation of remotely operated vehicles (ROVs). The training subset consists of a large number of synthetic images with 6D pose ground truth for ROVs. These synthetic images are generated using BlenderProc and further rendered with the underwater neural rendering (UWNR) strategy to enhance their realism. The testing subsets cover different real-world scenarios, including the Pool subset and Maoming subset, focusing on challenging cases that involve partial occlusion and low visibility. Diverse recent methods are evaluated on the constructed dataset. The results show that methods based on dense coordinates currently perform best, outperforming both the keypoint-based method and the refinement-based method. Our dataset will be made publicly available soon.

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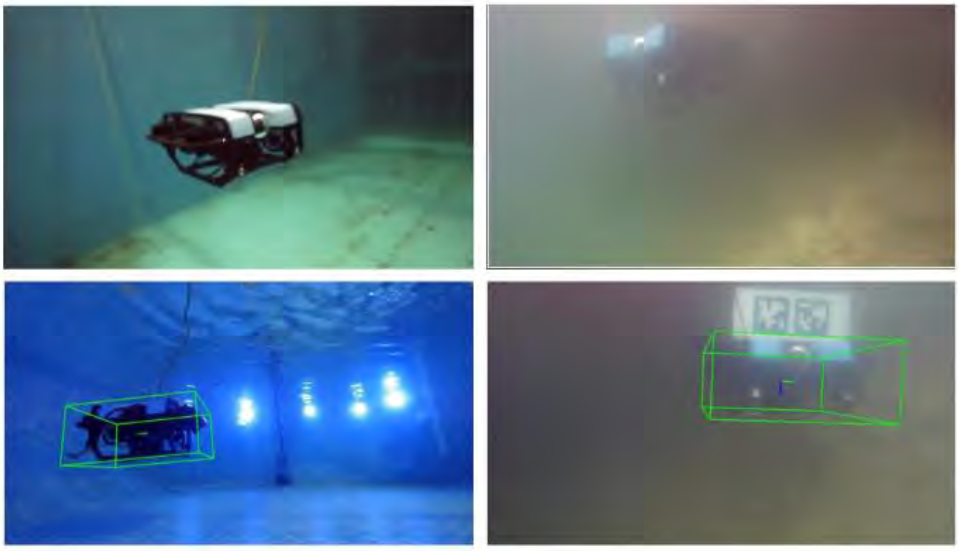

Fig. 1. The BlueROV Heavy is commonly utilized underwater, such as conducting experiments in engineering pools (left) and exploring the open lakes (right). We can provide the 6D pose annotations obtained through a motion capture system or a marker-based system (bottom). The green wireframe represents the projection of the 3D bounding box of the ground-truth pose.

How NOKOV Contributes to the Research

The experimental pool with a dimension of about 6.0×3.5×1.5m is equipped with a NOKOV motion capture system, which supports the capture area of about 4.0×2.5×1.0m and tracks the reflective markers on the ROV with millimetre precision, enabling accurate annotations collection.

Citation J. Tang et al., "ROV6D: 6D Pose Estimation Benchmark Dataset for Underwater Remotely Operated Vehicles," in IEEE Robotics and Automation Letters, vol. 9, no. 1, pp. 65-72, Jan. 2024, doi: 10.1109/LRA.2023.3331624.

Link https://ieeexplore.ieee.org/document/10313927

RUSSO: Robust Underwater SLAM with Sonar Optimization against Visual Degradation

Keywords

Forward-looking imaging sonar, underwater simultaneous localization and mapping (SLAM), visual degradation

Abstract

Visual degradation in underwater environments poses unique and significant challenges, which distinguishes underwater simultaneous localization and mapping (SLAM) from popular vision-based SLAM on the ground. In this article, we propose robust underwater SLAM with sonar optimization (RUSSO), a robust underwater SLAM system, which fuses stereo camera, inertial measurement unit (IMU), and imaging sonar to achieve robust and accurate localization in challenging underwater environments for 6 degrees of freedom (DoF) estimation. During visual degradation, the system is reduced to a sonar-inertial system estimating 3-DoF poses. The sonar pose estimation serves as a strong prior for IMU propagation, thereby enhancing the reliability of pose estimation with IMU propagation. In addition, we propose a SLAM initialization method that leverages the imaging sonar to counteract the lack of visual features during the initialization stage of SLAM. We extensively validate RUSSO through experiments in simulator, pool, and sea scenarios. The results demonstrate that RUSSO achieves better robustness and localization accuracy compared to the state-of-the-art visual-inertial SLAM systems, especially in visually challenging scenarios. To the best of authors' knowledge, this is the first time fusing stereo camera, IMU, and imaging sonar to realize robust underwater SLAM against visual degradation.

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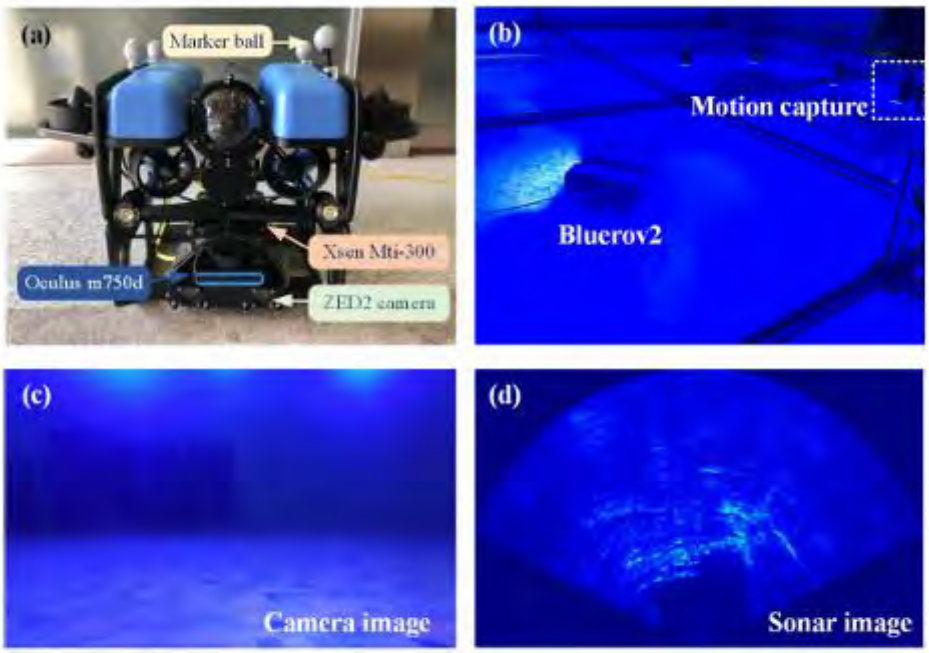

Fig. 7. (a) Experimental platform of ours. (b) Experiment environment in pool setting up with motion capture system. (c) ZED2 camera image in the pool. (d) Oculus m750 d image in the pool.

How NOKOV Contributes to the Research

Apart from the simulator experiments, we also conduct realworld experiments in a lab pool. The pool is about 3m in width and 7m in length. A motion capture system NOKOV with 12 underwater cameras mounted in the pool is used to provide the ground truth poses of the underwater robot, as shown in Fig.8(b). We use a Bluerov2 robot with eight-thruster configurations as the robot platform. The robot is equipped with a ZED2 stereo camera, a high-precision Xsens MTi-300 IMU, and Oculus m750d imaging sonar, as shown in Fig. 8(a). Sample camera and sonar images obtained in the pool are shown in 8(c)-(d).

Citation Pan S, Hong Z, Hu Z, et al. Russo: Robust underwater slam with sonar optimization against visual degradation[J]. IEEE/ASME Transactions on Mechatronics, 2025.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001470453600001

Safety analysis of floating multi-module systems under connector failure

Keywords

Floating multi-module (FMM) systems, Connector failure, Maximum motion response, Modal characteristics, Motion trajectory, Maximum line tension

Abstract

Floating multi-module (FMM) systems, like floating offshore photovoltaic and floating city, provide an innovative solution to challenges posed by resource scarcity and population growth. These systems consist of multiple identical floating modules, interconnected by connectors and anchored by a mooring system. Connectors, as critical components, are vulnerable to failure due to factors such as extreme and cyclic loads. Such failures can result in accidents like module overturns, collisions, and mooring line failures, which threaten the safety of engineering structures. Therefore, a numerical model of an FMM/connector/mooring system was established, based on 3-D potential flow and multi-body dynamic theory, to investigate the effects of connector failure on system safety. A model test was conducted to validate the accuracy of the developed numerical model. The numerical results show that the maximum surge, sway, and yaw motions are notably increased by connector failure, particularly in the weather-side modules connected to the failed connector. Furthermore, the modal characteristics of the system are markedly changed after failure, with the amplitude curves for surge, sway, and yaw exhibiting multiple peaks, increasing the resonance risk of engineering structures. Meanwhile, due to the connector failure, the horizontal motion trajectories of the modules are transformed from straight lines into complex patterns, such as ellipses or '∞'-shapes. Finally, the maximum tensions in the remaining connectors positioned opposite the failed connector are considerably higher than those observed under intact conditions, increasing the risk of cascade connector failures and consequently endangering the safety of engineering structures.

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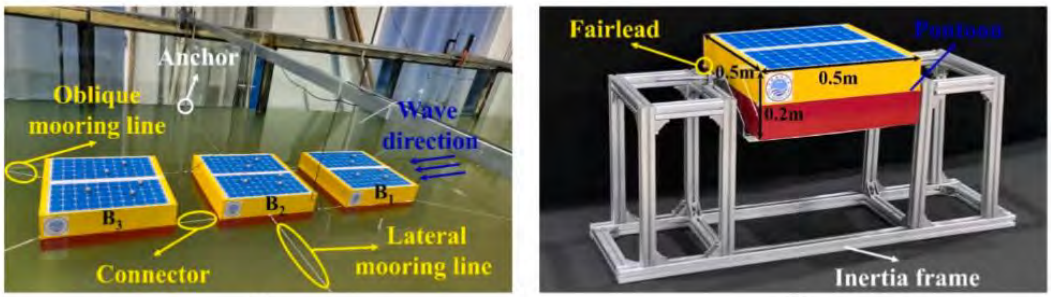

(a) (b)

Fig. 4. Physical model of the FMM system. (a) The whole system; (b) a single module.

How NOKOV Contributes to the Research

3.2. Numerical model validation
A model test, as illustrated in Fig. 3, was conducted to verify the accuracy of the numerical model. The model test was carried out in the wave flume at the Ocean University of China. The flume measures 60.0 m in length, 3.0 m in width, and 1.5 m in height. A paddle-type wave maker, located at one end of the flume, is capable of generating regular waves with various periods and heights. A wave absorber is installed at the opposite end to minimize wave reflection. A length scale ratio of 1:10 is adopted for the model test according to the Froude similarity criterion. Table 3 presents the model-scale parameters for a single module. Since the restoring force acting on the modules mainly depends on the axial stiffness and length of the mooring lines, and their mass and diameter are relatively small, the key objective is to ensure that stiffness and length meet the scaling requirements. Table 4 summarizes the main properties of the mooring lines and connectors in the scaled FMM system. Fig. 4 shows the physical model of the FMM system and a single module. The NOKOV motion capture system was used to record the time series of module motions, while SIMBATOUCH tension sensors were employed to measure the tension time series in the connectors and mooring lines.

Citation Cai, Hongyong, De-Qing Zhang, Junfeng Du, Zhi-Ming Yuan, and Zhenqiang Jiang. "Safety analysis of floating multi-module systems under connector failure." Engineering Structures 349 (2026): 121916.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001639726600001

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The Foldable Fin With Dynamic Adjustments for Manta Ray-Inspired Robots

Keywords

Bio-inspired robots, mechanical design, foldable fin, manta ray-inspired robots

Abstract

Biological manta rays alter the projected area of their pectoral fins during flapping, achieve different flapping strokes to adjust dynamic generation, such as holding, rising, sinking and rolling strokes. Manta ray-inspired robots possess high motion efficiency and stability, exhibiting broad prospects in underwater applications. A manta ray-inspired robot capable of projected area variations can gain more agility to adapt to complex environments. However, the fin structures of existing manta ray-inspired robots primarily serve to support and drive the flexible skin to flap, lacking the ability to vary the projected area. To achieve diverse flapping strokes, robots typically rely on multiple servos and complex algorithms to adjust each servo's motion parameters. In this article, we propose a foldable fin for manta ray-inspired robots, structurally varies the robot's span to adjust dynamic generation under simple control. The foldable fin is designed by linkage mechanisms, where three foldable modules are modularly meshed through tooth profiles, enabling synchronized folding and extending along a carbon spar. These design achieve a weight of 95 g with high stiffness, and a 78.75% foldable ratio with rapid operation. The kinematics of the foldable fin are modeled to describe different strokes. Underwater tests demonstrate that the maximum length of the foldable fin exhibits significant increase in lift and thrust compared to its minimum length in symmetric strokes, while asymmetric strokes exhibit significant adjustments in dynamics. Swimming validations further confirm the propulsion capability of the foldable fin, highlighting its potential to enhance the agility of manta ray-inspired robots.

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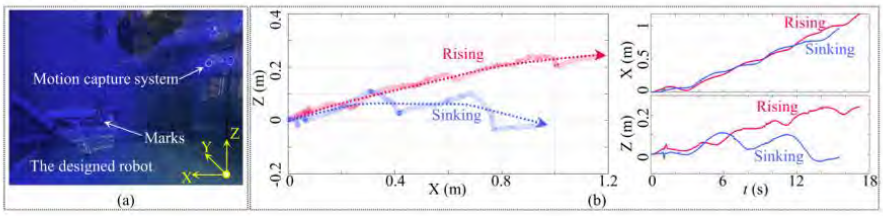

Fig. 10. Swimming validations for demonstrating the fin's dynamic adjustments. (a) The robot is swimming in a $3 \times 4 \times 1.5$ m pool, while a motion capture system tracks the positions and velocities of multiple marks attached to the robot's body. (b) At $f = 0.2$ Hz and $A = 25°$, the robot achieved noticeable vertical displacements during both rising and sinking behaviors, while maintaining a forward swimming speed of 0.09 m/s.

How NOKOV Contributes to the Research

Additionally, for the rising and sinking behaviors, as the primary objective is to accurately capture the robot's three-dimensional trajectory without the need for recording servo currents via wired connections, the corresponding tests are conducted in an another 3 m (width) × 4 m (length) × 1.5 m (depth) pool equipped with a motion capture system (Mars4H UW, NOKOV Science & Technology Co., Ltd.) \[Fig. 10(a)]. At a flapping frequency around 0.2 Hz and an amplitude of 25°, the tracking results show that both behaviors achieve significant vertical displacement while maintaining a forward swimming velocity of 0.09 m/s \[Fig. 10(b)].

Citation Y. Xiang, L. Gu, K. Ye, Z. Zhang, Z. Gong and B. Tao, "The Foldable Fin With Dynamic Adjustments for Manta Ray-Inspired Robots," in IEEE Robotics and Automation Letters, vol. 10, no. 8, pp. 8107-8114, Aug. 2025, doi: 10.1109/LRA.2025.3583504.

Link https://webofscience.clarivate.cn/wos/woscc/full-record/WOS:001521457100011

UTracker: Learning Visuomotor Policies for Underwater Active Target Tracking via Imitation Learning and Diffusion Model

Keywords

Underwater active target tracking, reinforcement learning, imitation learning, diffusion model

Abstract

Active visual tracking of underwater non-cooperative targets is a challenging task for autonomous underwater vehicles (AUVs) due to the complexity of underwater environments and the unpredictable dynamics of target motion. To address this challenge, this letter proposes UTracker, a novel framework for learning visuomotor policies tailored to underwater active target tracking. UTracker employs a two-stage training pipeline to enhance data efficiency and generalization. First, a state-based expert policy is trained in simulated underwater environments to perform underwater target tracking, and then used to generate paired image-action data as expert demonstrations. Second, a visuomotor policy is distilled from expert demonstrations via imitation learning, with diffusion models incorporated to refine action sequences and improve robustness against observation noise and dynamic perturbations. Extensive simulation studies show that UTracker outperforms baseline methods in challenging underwater scenarios. Moreover, sim-to-real experiments on a real AUV validate that the learned visuomotor policy reliably tracks non-cooperative targets in real-world environments.

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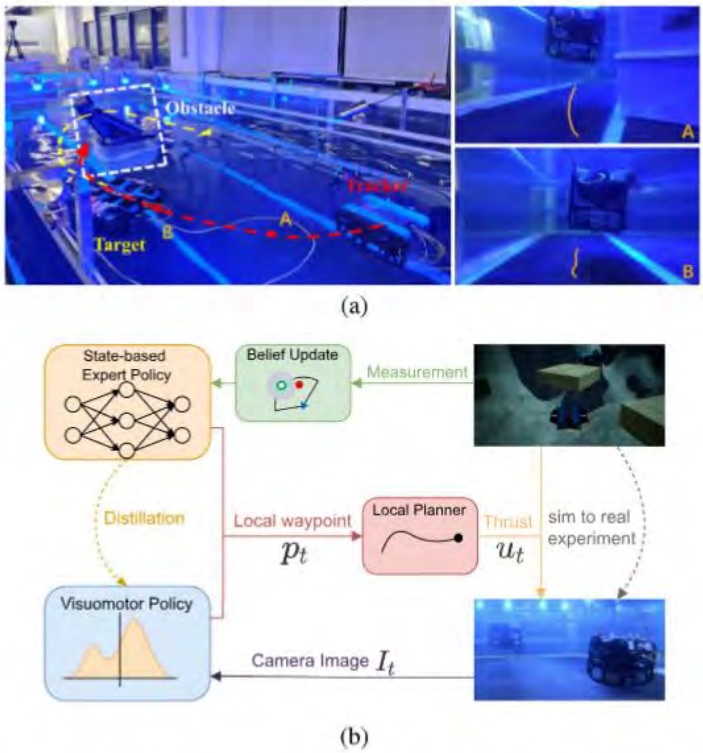

Fig. 1. (a) Visualization of the tracker AUV trajectory (red, governed by the visuomotor policy learned with UTracker) and target trajectory (yellow, predefined) in the UATT task. (b) Conceptual overview of the proposed UTracker framework. A visuomotor policy for UATT is distilled from the data collected by a state-based expert policy via IL and a diffusion model. Using only egocentric image observations, the policy generates local waypoints for the tracker's low-level controller.

How NOKOV Contributes to the Research

Local waypoints generated by πdπd were transformed into global coordinates using motion-capture poses. These were then converted via MAVROS \[35] into joystick-override commands for the AUV autopilot. The policy ran on an on-shore workstation (NVIDIA RTX 4060), communicating with the AUV via a shared ROS network over Ethernet.

Citation Meng A, Hong L, Feng Y, et al. UTracker: Learning Visuomotor Policies for Underwater Active Target Tracking Via Imitation Learning and Diffusion Model[J]. IEEE Robotics and Automation Letters, 2026.

Link https://ieeexplore.ieee.org/document/11394786

Vertical Object Grasping Method for an AUV Equipped with a Monocular Camera and a Gripper

Keywords

Autonomous Underwater Vehicle (AUV), Grasping, Object Detection

Abstract

Autonomous Underwater Vehicles (AUVs) are increasingly used for underwater operations, including intervention tasks such as inspection and sample collection. This study proposes a method for an AUV to grasp a vertical cylindrical object using a monocular camera and a gripper. Image processing extracts key features, estimating relative distance and angle for PID-based control. The approach was validated in simulations and water tank experiments, demonstrating successful grasping. The method is applicable to docking, perching, and sensor deployment. Future work will enhance image recognition and control for real-sea operations, improving AUV intervention capabilities in complex underwater environments.

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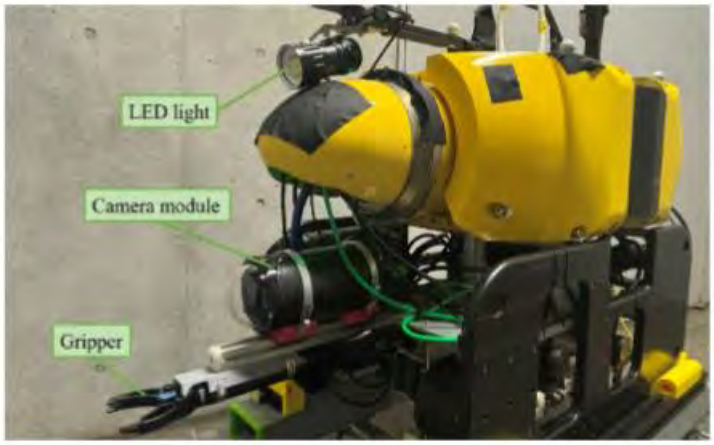

Fig.5: The AUV Tri-TON equipped with the camera module and the gripper.

How NOKOV Contributes to the Research

3.3 水槽実験本手法が実機でも適用できることを確認するため，東京大学生産技術研究所の 7x7x8m 水槽にて実機を用いた水槽実験を行った.Tri-TON 及びタ-ゲットの位置は水中モ-ションキャプチャ NOKOV による測定値を真値として扱い，シミュレ-ションと同様の条件で計測を行った.

Citation Motoki SAKAI, Sehwa CHUN, Yuichi MOTEGI, Toshihiro MAKI, Vertical Object Grasping Method for an AUV Equipped with a Monocular Camera and a Gripper, The Proceedings of JSME annual Conference on Robotics and Mechatronics (Robomec), 2025

Link https://www.jstage.jst.go.jp/article/jsmermd/2025/0/2025_2P2-D09/_article/-char/en

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Visual-Inertial Fusion-Based Five-Degree-of-Freedom Motion Measurement System for Vessel-Mounted Cranes

Keywords

stereo camera; object detection; IMU; Kalman filtering

Abstract

Vessel-mounted cranes operate in complex marine environments, where precise measurement of cargo positions and attitudes is a key technological challenge to ensure operational stability and safety. This study introduces an integrated measurement system that combines vision and inertial sensing technologies, utilizing a stereo camera and two inertial measurement units (IMUs) to capture cargo motion in five degrees of freedom (DOF). By merging data from the stereo camera and IMUs, the system accurately determines the cargo's position and attitude relative to the camera. The specific methodology is introduced as follows: First, the YOLO model is adopted to identify targets in the image and generate bounding boxes. Then, using the principle of binocular disparity, the depth within the bounding box is calculated to determine the target's three-dimensional position in the camera coordinate system. Simultaneously, the IMU measures the attitude of the cargo, and a Kalman filter is applied to fuse the data from the two sensors. Experimental results indicate that the system's measurement errors in the x, y, and z directions are less than 2.58%, 3.35%, and 3.37%, respectively, while errors in the roll and pitch directions are 3.87% and 5.02%. These results demonstrate that the designed measurement system effectively provides the necessary motion information in 5-DOF for vessel-mounted crane control, offering new approaches for pose detection of marine cranes and cargoes.

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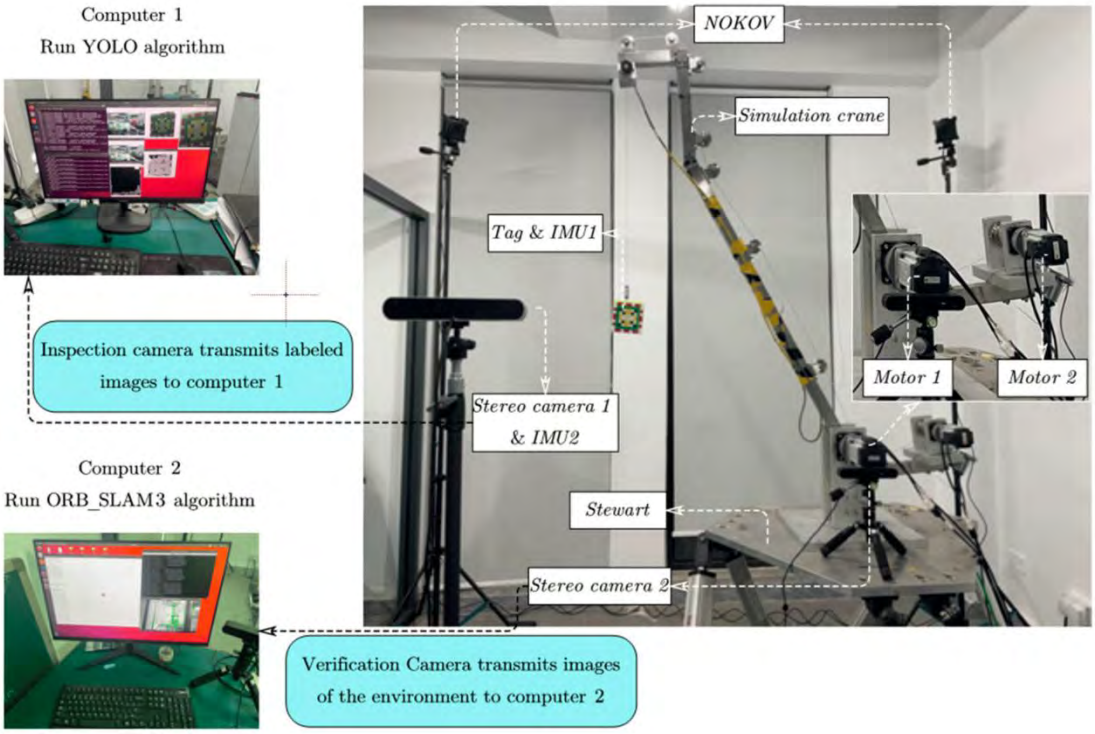

How NOKOV Contributes to the Research

To assess the accuracy of measurements during the experiment, results measured by the NOKOV motion capture system composed of eight Mars2H were used as the ground truth.

Citation Yu, B.; Cheng, Y.; Xia, X.; Liu, P.; Ning, D.; Li, Z. Visual-Inertial Fusion-Based Five-Degree-of-Freedom Motion Measurement System for Vessel-Mounted Cranes. Machines 2024, 12, 748. https://doi.org/10.3390/machines12110748

Link https://www.mdpi.com/2075-1702/12/11/748

Conceptual design and numerical analysis of mooring in-situ power generation systems under low current velocity conditions

Keywords

Deep sea; In-situ power generation system; Ocean current energy; Ductless Archimedes screw turbine; Mooring system

Abstract

This study proposes a mooring in-situ power generation system harnessing low-speed ocean current energy, with a focus on numerical investigations into its hydrodynamic stability and power output capacity. The mooring configuration effectively addresses sediment issues common to conventional seabed-mounted installations, while enhancing the operational flow velocity range for improved energy capture efficiency. A ductless Archimedes screw turbine serves as the primary energy extraction component, realizing the efficient use of low-speed ocean current energy. An integrated numerical model, coupling mooring lines with turbine dynamics and validated through experiments, was employed in this study. Comparative analysis was conducted for single-line mooring system and four-line mooring system with distinct performance characteristics. Under the low-flow condition of 0.3 m/s, both two mooring systems demonstrate excellent power output capacity. The single-line mooring system achieves a Cp,a of 0.363, while the four-line configuration attains a higher Cp,a of 0.376. Parametric studies on inflow angles revealed different characteristics: the single-line mooring system accommodates wider yaw variations to adapt to the incoming currents, whereas the four-line mooring system demonstrates bidirectional current utilization capability with enhanced dynamic stability. These findings provide valuable design guidelines for optimizing mooring systems in deep-sea renewable energy applications.

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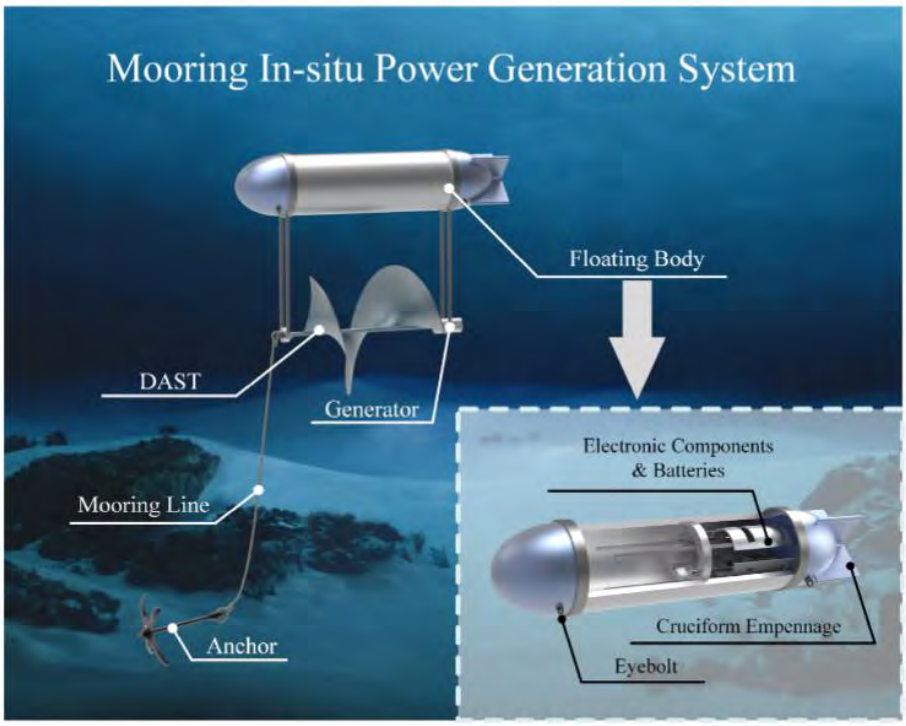

Fig. 1. Schematic diagram of the mooring in-situ power generation system.

How NOKOV Contributes to the Research

Motion capture technology (NOKOV) was utilized to measure the attitude changes of the floating body under incoming flow conditions. This technology employs cameras to track and record the motions of the floating body. The motion capture system adopted in this experiment primarily consisted of reflective markers, underwater cameras (MARS1.3HW UW), and motion capture software (as illustrated in Fig. 10). Reflective markers were affixed to the cross-shaped tails of the floating body to ensure robust visibility across multiple viewing angles. Underwater cameras record the model's position by tracking these markers. Through multi-camera localization of the markers, three-dimensional coordinates were calculated using programmed algorithms, thereby obtaining the floating body's instantaneous posture and motion data. The motion capture technology provides a measurement accuracy of approximately 0.1 mm, enabling reliable resolution of small amplitude motions. By combining the reconstructed marker positions with the predefined marker geometry, the instantaneous 6-DOF motions of the floating body were obtained.

Citation Wang Y, Zhang D, Li M, et al. Conceptual design and numerical analysis of mooring in-situ power generation systems under low current velocity conditions[J]. Ocean Engineering, 2026, 355: 125108.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001724514200001

Experimental study on the hydrodynamic characteristics and power performance of a novel Wind–Wave hybrid system based on a composite bucket foundation

Keywords

Wind–wave hybrid system; Physical model test; Composite bucket foundation; Energy capture; Hydrodynamic performance; Multi-body interference effects

Abstract

This study experimentally investigates the hydrodynamic coupling and energy capture mechanisms of novel wind – wave hybrid systems supported by a composite bucket foundation (CBF) with an energy-focusing structure. The effects of wave parameters and constant power take off (PTO) damping on motion response and power performance were analyzed. An interference coefficient was introduced to quantify multi-body interaction and to reveal the nonlinear hydrodynamic regulation within the system. Results show that lateral buoys impose a distinct frequency-dependent influence on the wave-ward side buoy. Constructive interference enhances the primary frequency response under short period waves. The phase-difference response remains insensitive to wave height, suggesting that a phase-based PTO control strategy has strong generality and simplifies parameter tuning in complex seas. Increasing wave steepness strengthens higher harmonics and nonlinear effects. However, multi-body interference concentrates energy at the fundamental frequency and suppresses second order components. Both hybrid systems display an optimal PTO damping. For the CBF–microarray, adaptive PTO tuning becomes necessary under short period waves and strong interference to ensure efficient energy conversion. This configuration demonstrates particularly advantageous performance in nearshore, short period environments such as Xiaomai Island. These findings provide practical guidance for design and field deployment of future hybrid systems.

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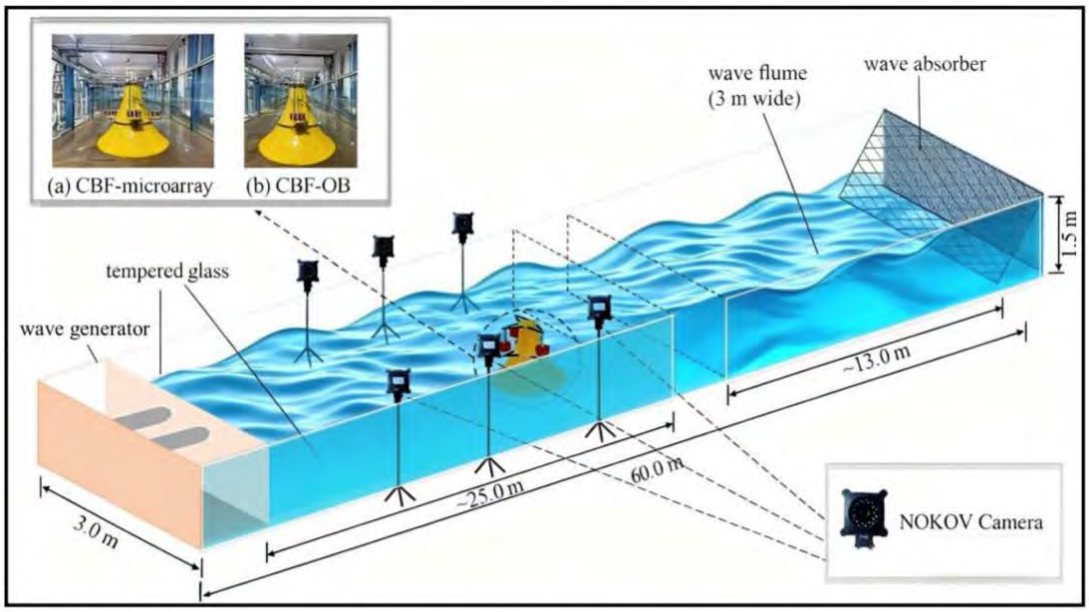

Fig. 3. Side view of the physical model test conducted in the wave flume at the Shandong Provincial Key Laboratory of Ocean Engineering.

How NOKOV Contributes to the Research

To capture the transient motion response of the buoy under wave action, a NOKOV Motion Capture Systems was employed. The system comprises six MARS9H high speed cameras, a POE powered network switch, a control unit, and the real time data processing software XINGYING 3.0 (https://www.nokov.com/), enabling high precision three dimensional motion measurement (Fig. 5). It provides spatial positioning accuracy better than 0.1 mm and temporal latency below 3 ms, effectively capturing subtle oscillations and phase variations of the buoy. In combination with other sensors, the system operated at a sampling frequency of 200 Hz.

Citation Song H, Yu T, Zhao X, et al. Experimental study on the hydrodynamic characteristics and power performance of a novel Wind–Wave hybrid system based on a composite bucket foundation[J]. Ocean Engineering, 2026, 350: 124316.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001673560500001

UW-MBSM: Multi-binocular vision system with non-overlapping fields of view-based underwater kinematic state measurement framework

Keywords

Underwater kinematic state measurement; Underwater binocular vision system; Underwater robots; Refractive camera model

Abstract

Accurate and real-time measurement of underwater robot kinematics is essential for the development and verification of advanced motion-control strategies. This paper presents UW-MBSM, a framework for accurate kinematic state measurement of underwater robots, which is implemented using a multi-binocular vision system with non-overlapping fields of view. The system integrates an imaging model for non-overlapping binocular groups, a refraction compensation model for multi-interface underwater imaging, and a fast circular coded marker detection algorithm optimized for degraded underwater visual conditions. A rigid-body-aware Kalman filtering strategy is further introduced to fuse trajectories of multiple markers and recover temporally consistent position, velocity, and acceleration. Experiments conducted in realistic underwater settings demonstrate that UW-MBSM achieves accurate, robust, and real-time kinematic measurement over an extended workspace.

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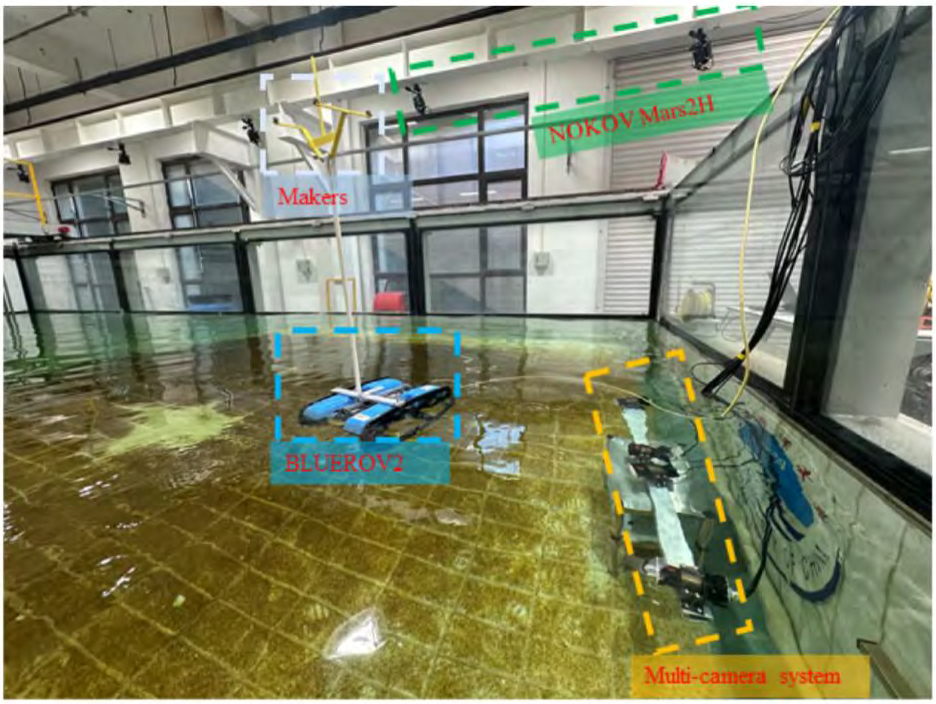

Fig. 24. Experimental setup for multi systems measurement comparison.

How NOKOV Contributes to the Research

To further evaluate the effectiveness of the proposed UW-MBSM framework, comparative experiments are conducted against a commercial optical motion capture system (NOKOV Mars2H), the onboard inertial sensing suite of the robot (IMU and AHRS), and a vision-based baseline method without underwater refraction compensation.
The experimental setup is illustrated in Fig. 24. A water tank is placed at the center of the laboratory, and sixteen NOKOV Mars2H cameras are arranged around the tank to provide full coverage of the workspace. An acrylic rod is rigidly attached to the BlueROV2 platform, with four reflective optical markers mounted on the top of the rod and kept strictly above the water surface for motion capture. This setup ensures that the Mars2H system operates entirely in an air medium, avoiding underwater refractive distortions. The UW-MBSM system is deployed on one side of the tank. During the experiment, the ROV performs free motion within the overlapping field of view of the motion capture system and the UW-MBSM system. Data from all systems are temporally aligned using timestamps prior to comparison.

Citation Jia W, Xie Z, Huang Y, et al. UW-MBSM: Multi-binocular vision system with non-overlapping fields of view-based underwater kinematic state measurement framework[J]. Measurement, 2026, 269: 120595.

Link https://www.sciencedirect.com/science/article/pii/S0263224126003040

A novel velocity guidance law for 3-D trajectory tracking of underactuated autonomous underwater vehicles: Theory, simulations and experiments

Keywords

Velocity guidance lawThree-dimensional trajectory trackingPrescribed performanceUnderactuated autonomous underwater vehicleAttitude stabilization in SO(3)

Abstract

Due to the lack of side thrusters, three-dimensional trajectory tracking control of underactuated autonomous underwater vehicles (AUVs) presents a significant challenge. current solutions, such as angular guidance and feedback linearization, often suffer from delayed responses or overly complex models. to overcome these limitations, this paper proposes a novel velocity guidance law (VGL) derived by the backstepping method. compared to existing guidance approaches, the proposed method reduces complexity while ensuring accurate trajectory tracking. A rigorous theoretical analysis is conducted to guarantee the stabilization of both position and orientation, effectively addressing the backward motion phenomenon observed in prior studies. for operations in constrained environments, the proposed method is extended with prescribed performance to maintain tracking errors within predefined time-varying bounds. additionally, an adaptive velocity control strategy based on nonlinear disturbance observer is proposed without assuming bounded uncertainties. simulation and experimental results demonstrate the effectiveness and superior performance of the proposed methods compared to existing techniques

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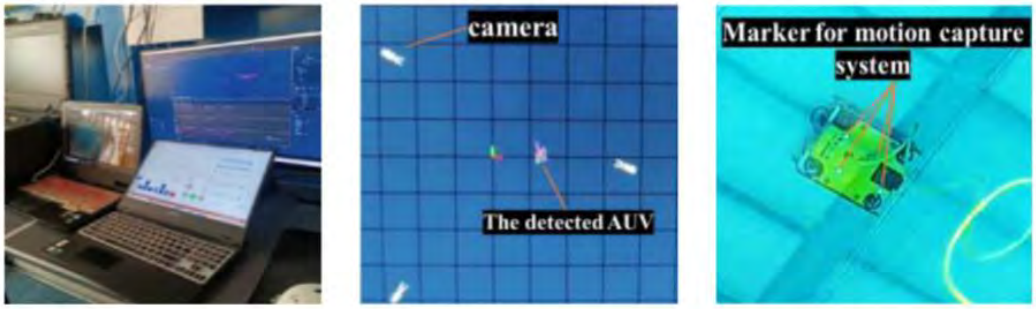

Fig. 10. The upper computer, motion capture system and the tested AUV.

How NOKOV Contributes to the Research

In the experiments, the AUV is controlled with a 100 ms sampling time. The horizontal position of AUV is measured by NOKOV motion capture system (a commercial motion capture system, please refer to https://en.nokov.com/about.html) as shown in Fig. 10. The depth is measured by a depth sensor, and the attitude is measured by a strap-down inertial navigation system (SINS) with a sampling rate of 100 Hz. The raw 100-Hz SINS data is mean-filtered. In addition, feedback from these sensors is processed through a low-pass filter, i.e. \(\dot{X}_L = 4(X - X_L)\), where \(X = [\eta^T \ v^T]\) represents the feedback and \(X_L\) is output of the filter. Note that the filter's time constant should be much smaller than the AUV's response time.

Citation Chen H, Ye Z, Tang G, et al. A novel velocity guidance law for 3-D trajectory tracking of underactuated autonomous underwater vehicles: Theory, simulations and experiments[J]. Automatica, 2026, 190: 113084.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001781771400002

Fully flexible triboelectric proprioceptive sensor for online state estimation of underactuated underwater robots

Keywords

Proprioceptive perception; Triboelectric nanogenerators; Self-powered; Robotic fish

Abstract

Fish possess sophisticated proprioceptive systems that enable sensitive detection of external flow fields and monitoring of their own motion states. Inspired by this biological mechanism, robotic fish equipped with proprioceptive sensing are capable of perceiving the positions of their body and fins, thereby facilitating precise control of their actuators. This capability requires flexible sensors embedded in the robotic fish body that can operate reliably and stably in marine environments. In this study, a fin-like soft triboelectric proprioceptive sensor (STPS) was developed to enable posture assessment, further equipping an underwater robot with simultaneous trajectory estimation capabilities through an analytic deep learning framework. The device consists primarily of the soft fin-like shell made from silicone rubber and three triboelectric sensing units. Air chamber technology is incorporated into the soft shell to reduce signal interference caused by ions in water. The distributed arrangement of the sensing units allows the STPS to estimate swing posture and detect external disturbances, offering a sensitivity of 0.028 V/alpha and a response time of 81 ms. Furthermore, the STPS is integrated into an underwater robot, where deep learning techniques are employed to map STPS signals to the robot's motion trajectory, with a root-mean-square error of 0.15 mm and a verification loss of 0.01. These results indicate that the STPS provides an effective solution for online estimation of motion state and trajectory in underwater robots.

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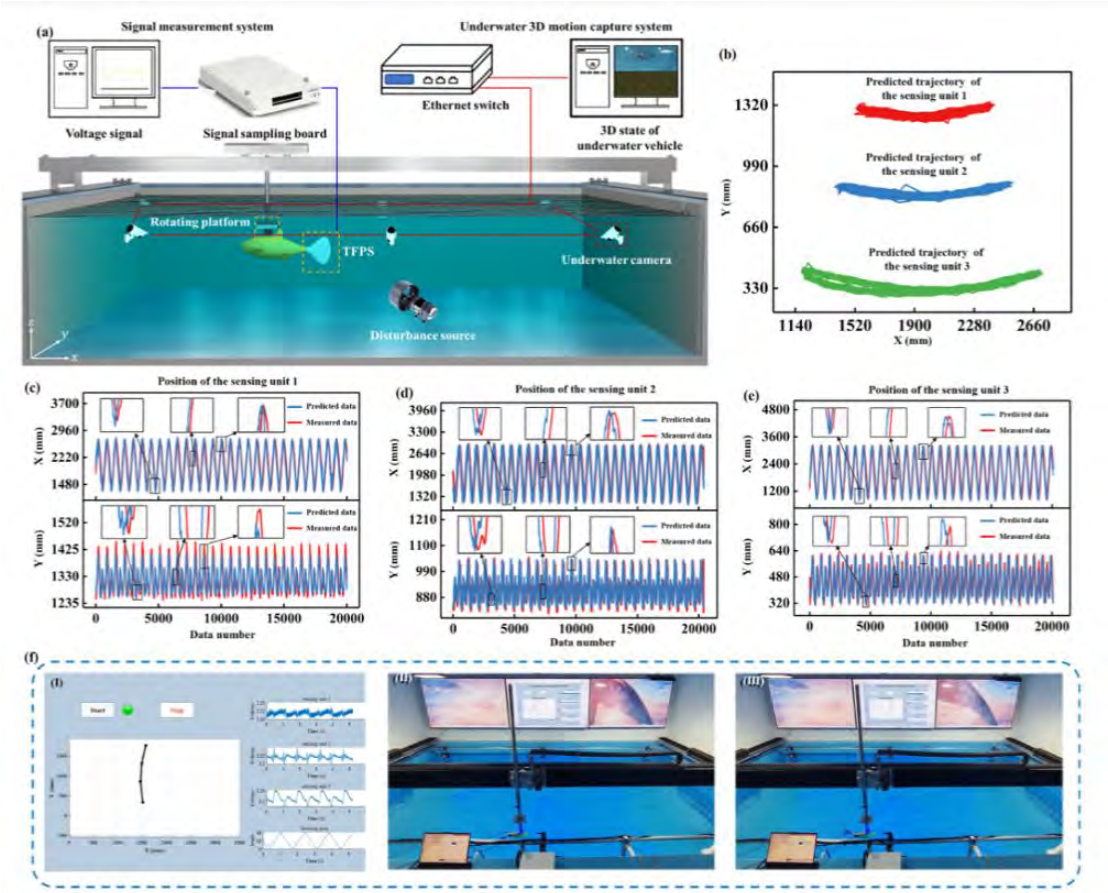

Fig. 4. Posture of the STPS in the multi-functional water pool. (a) Basic structures of the experiment platform, showing a signal sampling system and an underwater motion capture system. (b) Swinging posture of the three sensing units. (c) Swing trajectories of the sensing unit 1. (d) Swing trajectories of the sensing unit 2. (e) Swing trajectories of the sensing unit 3. (f) Real-time monitoring interface of the STPS.

How NOKOV Contributes to the Research

In order to effectively extract the swinging posture of the STPS, it is necessary to establish a dataset correlating the self-powered signal with the STPS posture. the BRF integrated with the STPS is mounted on a rod that allows depth adjustment in a multifunctional water tank, as shown in Fig. 4a. The underwater measurement system mainly consists of two parts: a signal sampling system used to obtain the output signals of the STPS, and an underwater motion capture system, known as Nokov, is utilized. To ensure that the motion capture system accurately captures the swinging posture of the STPS, markers are attached at the positions of the sensing units.

Citation Xu P, Li Y, Liu J, et al. Fully Flexible Triboelectric Proprioceptive Sensor for Online State Estimation of Underactuated Underwater Robots[J]. Sensors and Actuators A: Physical, 2026: 117981.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001769094600001

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Research on improving heave compensation accuracy based on inertial measurement unit error correction

Keywords

Error correction; Heave compensation system; Inertial measurement unit; Support vector machine; Back propagation neural network

Abstract

The compensation accuracy of deep-sea floating operation heave compensation systems is greatly affected by the accuracy of the sensors used for measurement. As the core sensor of these systems, the Inertial Measurement Unit (IMU) typically exhibits a heave detection error of approximately 5 cm, which hinders the system from meeting the required 95% compensation rate. This paper investigates methods to improve heave compensation accuracy by correcting IMU errors. First, this paper proposes two IMU's error correction algorithms: support vector machine classification and back propagation neural network fitting and establishes an IMU error detection system. Finally, a direct-drive winch-type heave compensation simulation test bench is established. The experimental results prove that the two error correction methods can improve the heave compensation rate by 8.8% and 11.7%, respectively, without relying on external reference signals. This provides an effective technical path for improving the compensation accuracy of the heave compensation winch system and enhancing its economic efficiency.

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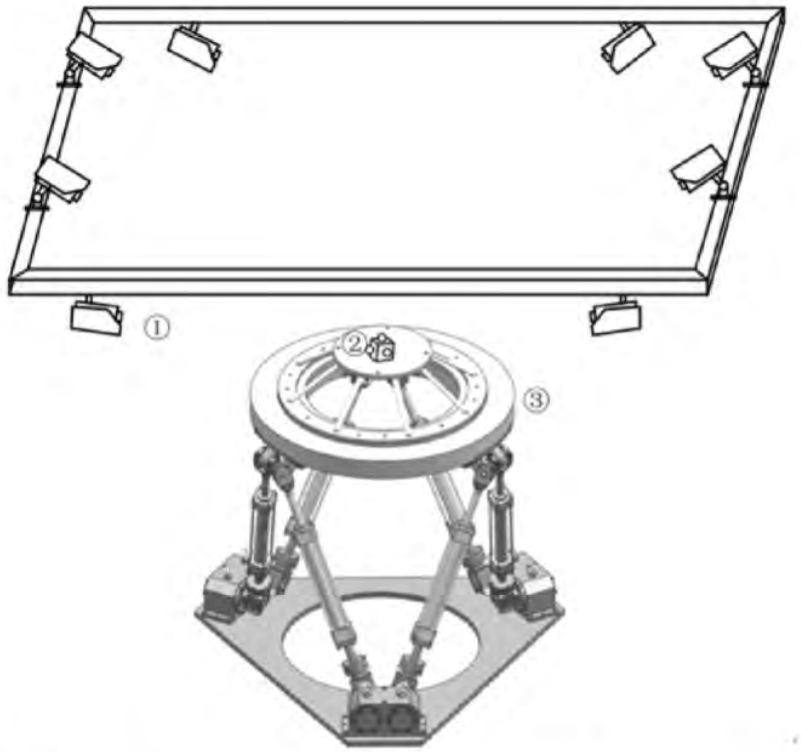

Fig. 1. IMU error detection system(①Visual motion capture system.②-IMU.③Six-degree-of-freedom platform).

How NOKOV Contributes to the Research

The IMU used in this paper is the Ekinox-A motion reference unit from SBG Systems of France, a tactical-grade MEMS inertial system with a typical acceleration range of ±16 g. According to the manufacturer's documentation, the heave measurement accuracy of this IMU is 5 cm. In this paper, the motion capture system adopted is the NOKOV Metric Motion Capture System (Mars series), achieving 3D accuracy of ±0.5 mm, which far exceeds the IMU precision employed in this experiment. Therefore, it is reliable to adopt this motion capture system as the agreed-upon ground truth. Finally, the motion platform employed in this study is a six-degree-of-freedom motion simulation platform developed by Harbin Institute of Technology, with heave displacement accuracy below 1 mm.

Citation Xiao T, Zhou Y, Quan Y. Research on improving heave compensation accuracy based on inertial measurement unit error correction[J]. Ocean Engineering, 2026, 359: 125965.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001767666500001

Ice-resistant performance evaluation of a downward-pressure-induced pile foundation for cold-region wind turbines Open Access

Keywords

VIBRATIONS; MODEL

Abstract

Sea-ice hazards in cold-region sea areas pose significant challenges to the structural safety of offshore wind turbines. Although traditional ice-resistant cone pile foundations can effectively reduce ice loads, their application to large-diameter piles involves a pronounced load trade-off: reductions in peak ice forces are often accompanied by substantial increases in wave loads. To address this issue, this study proposes a modular downward-pressure-induced (DPI) ice-resistant wind turbine foundation. A computational fluid dynamics-discrete element method coupled numerical framework, validated through scaled physical model experiments, is employed to investigate the dynamic evolution of broken ice interaction with the DPI foundation, including initial contact, accumulation-induced jamming, and subsequent dynamic release. The results show that while maintaining effective ice-resistant performance, the DPI foundation significantly reduces both horizontal and vertical wave loads, thereby alleviating the inherent design trade-off of conventional ice-resistant cone foundations, in which improved ice resistance is achieved at the expense of increased wave loading. Parametric sensitivity analysis further indicates that when the ice-guiding angle ranges from 25 degrees to 35 degrees and the circumferential arrangement angle ranges from 22.5 degrees to 30 degrees, the DPI foundation most effectively suppresses ice force-chain locking, resulting in optimal ice-resistant performance. This study provides useful insights for the coordinated control of ice and wave loads and for the lightweight design of pile foundations in cold-region environments.

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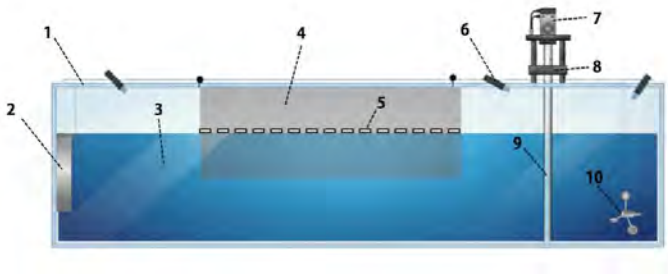

FIG. 2. Layout of the experimental system: 1-wave flume; 2-wave generator; 3-water; 4-anti-drift net; 5-model ice; 6-NOKOV camera; 7-force sensor; 8-sensor fixtures; 9-cylindrical monopile; and 10-LSH10-1S velocimeter.

How NOKOV Contributes to the Research

An LSH10-1S ultrasonic Doppler velocimeter was used to acquire flow-velocity information, and a NOKOV motion-capture camera system was employed to record the motion of broken ice, their accumulation patterns, and their collisions with the structure. In addition, to enhance the controllability of the incoming ice path and the stability of the measurement data, we installed auxiliary facilities, including sensor fixtures and an anti-drift net. The layout of the experimental system is shown in Fig. 2.

Citation Zhou C, Chen L, Liu W, et al. Ice-resistant performance evaluation of a downward-pressure-induced pile foundation for cold-region wind turbines[J]. AIP Advances, 2026, 16(6).

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001798876600001

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Hydrodynamic performance and layout analysis of a novel wind-wave hybrid system with composite bucket foundation and oscillating buoy microarray

Keywords

Composite bucket foundation; Microarray effect; Wind-wave hybrid system; Near-trapping; Hydrodynamic performance

Abstract

To address the intermittency of single renewable energy sources, this study proposes a wind-wave hybrid system combining a composite bucket foundation with an oscillating buoy microarray (CBF-microarray). A threedimensional numerical wave tank was established using the renormalization group (RNG) k-epsilon turbulence model and validated experimentally. This model was employed to investigate the hydrodynamic and energy output characteristics of different microarray layouts. The results show that microarray layout is a key parameter governing both energy synergy and structural safety. The buoy microarray provides effective shielding for the CBF, reducing the maximum wave run-up and pressure by up to 35.89%. However, wave interference among buoys can amplify local hydrodynamic responses. Clustered and symmetric layouts promote constructive superposition of diffracted and reflected waves between the CBF and buoys. This interaction induces a wave-locking effect, which prolongs wave energy residence time and enhances energy capture. Under optimal conditions, the maximum interaction factor reaches 3.434, and the total capture width ratio approaches 5.0. In contrast, configurations with strong energy concentration may trigger near-trapping wave phenomena. These conditions intensify local wave run-up and pressure and pose potential risks to structural safety. Among all configurations, the symmetric layout regulates diffraction and reflection interference between the CBF and buoys in a coordinated manner. It maintains high energy gain while suppressing excessive local hydrodynamic responses. This layout achieves an optimal balance between energy utilization efficiency and structural safety. The present findings provide a reference for the design and application of microarray layouts in wind-wave hybrid systems.

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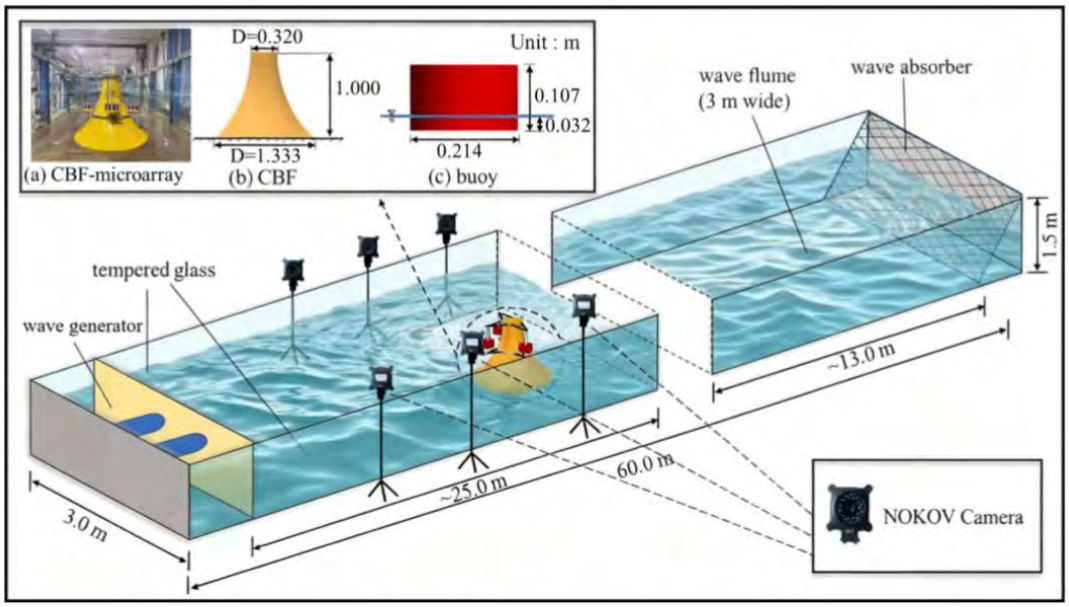

Fig. 8. Schematic diagram of the CBF–microarray experimental setup.

How NOKOV Contributes to the Research

The motion responses of the buoys were measured in real time using a NOKOV motion capture system. To validate the numerical model, both undamped and constant damping conditions were tested for ab=90∘a b =90∘ and adeg=0∘a deg =0∘. The corresponding experimental parameters are summarized in Table 2 and are used to assess the reliability and accuracy of the numerical results.

Citation Song H, Yu T, Zhang Z, et al. Hydrodynamic performance and layout analysis of a novel wind-wave hybrid system with composite bucket foundation and oscillating buoy microarray[J]. Energy, 2026: 141246.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001762720600001

Hydrodynamic mechanisms of energy-focusing and multi-body interference in composite bucket foundation-based wind–wave hybrid systems

Keywords

Composite bucket foundation; WEC microarray; Wind-wave hybrid system; Hydrodynamic coupling; Energy-focusing effect; Multi-body interference effect

Abstract

The composite bucket foundation (CBF), characterized by its large arc transition section, can reconstruct the local wave field, providing a new mechanism for wave energy regulation in wind-wave hybrid systems (WWHSs). This study investigates the novel CBF-based WWHSs. Dimensionless coefficients describing the energy-focusing effect, interference, and dual-interference mechanisms are introduced to evaluate the CBF energy-focusing and multi-body interference characteristics under various wave conditions, damping parameters, and system configurations. A harmonic energy decomposition method is further employed to reveal the evolution of the buoy motion response spectrum. The results show that the CBF reshapes the wave field and forms an energy convergence zone on the wave-ward side, thereby enhancing buoy energy capture. Under optimal conditions, the energy-focusing coefficient of the CBF-OB hybrid system reaches 5.679. Meanwhile, multi-body interference exhibits pronounced spatial selectivity. The wave-ward side buoy is almost unaffected, whereas the lateral buoys in the microarray experience energy suppression, with their RAO decreasing to 0.807 times that of a single buoy. The dual-interference mechanism in COBRA further amplifies the motion of the wave-ward side buoy to 2.672 times that of a single buoy, increasing energy capture by up to 5.770 times. Meanwhile, the lateral buoys show increased motion but not necessarily higher power output. In addition, the presence of the CBF induces energy transfer among harmonics, producing small secondary peaks near the dominant frequency and enhancing higher-order harmonic energy. These findings provide valuable insights for the coordinated exploitation of wind and wave energy in coastal regions such as Xiaomai Island.

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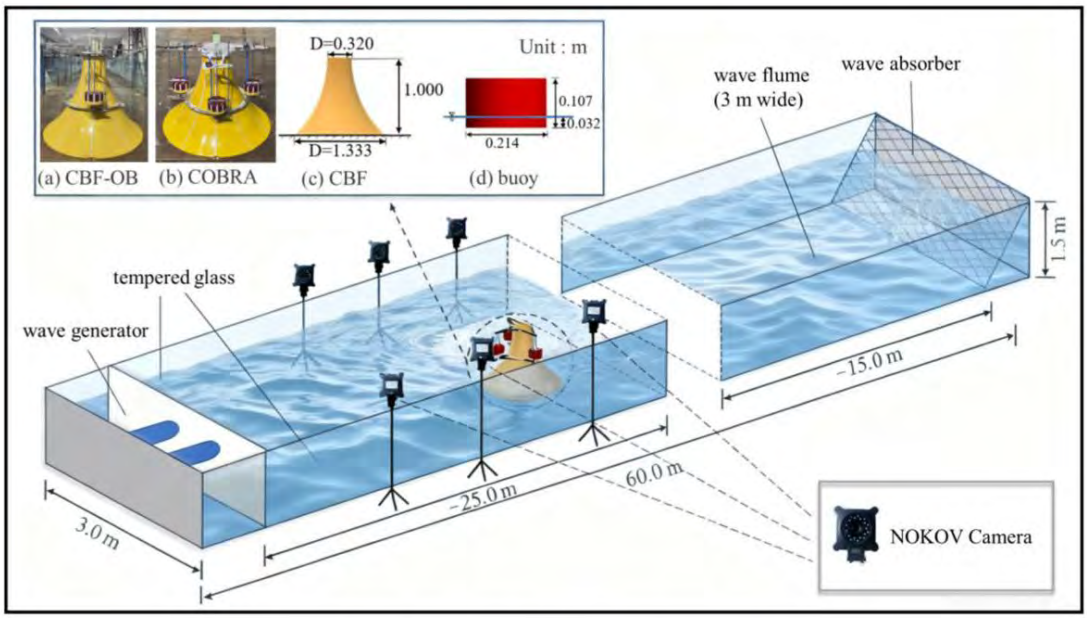

Fig. 3. Schematic diagram of the hybrid systems experimental setup.

How NOKOV Contributes to the Research

The arc transition section of the CBF are illustrated in Fig. 3(c). The cylindrical OBs had a density of 300 kg/m33 and a draft of 0.032 m (Fig. 3(d)). Buoy motions were measured using a NOKOV optical motion capture system, and a magnetic powder brake was used to simulate a constant PTO damping system (Fig. 4).

Citation Song H, Yu T, Xi Q, et al. Hydrodynamic mechanisms of energy-focusing and multi-body interference in composite bucket foundation-based wind – wave hybrid systems[J]. Energy, 2026, 358: 141375.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001778935800001

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浮式风机水池试验及叶片模型重构方法研究

关键词

浮式风机;模型试验;叶片缩尺模型;气动性能相似;

摘要

风电近年来在我国发展迅速,且资源丰富。随着陆上风电装机容量趋于饱和,海上风电凭借其诸多优势,被视为未来风电发展的主要方向,并受到广泛关注。随着海上风电开发水深的不断增加,风机支撑基础将逐渐从固定式向浮式转变。 浮式风机由浮式支撑平台的水动力学系统(包括系泊系统)和风机的空气动力学系统(包括塔架、机舱、叶轮转子等)组成,是一个高度复杂的双向耦合系统。缩尺模型试验是研究浮式风机动力学问题的有效手段,也是验证数值分析结果的重要途径。然而,由于傅汝德相似和雷诺相似难以同时满足,浮式风机模型的空气动力学性能和水动力学性能难以同时相似。本文针对以上进行了相关研究,主要工作包括: (1)针对浮式风机模型空气动力学性能不相似的问题,将第三代非支配排序遗传算法与前馈神经网络相结合,旨在确保模型风力发电机的推力与全尺寸模型匹配,并遵循傅汝德相似性原则。以 DTU 10MW 风机作为研究对象,利用遗传算法优化浮式风机叶片的弦长和扭转角度,得到满足推力相似性的叶片参数。通过遗传算法优化过程获得的数据用于训练前馈神经网络,前馈神经网络基于所需推力快速预测叶片设计参数。结果表明,基于前馈神经网络预测的叶片设计参数计算出的浮式风机推力与期望推力高度一致,验证了使用前馈神经网络进行快速叶片重建的可行性。 (2)针对浮式风机模型空气动力学性能不相似的问题,基于升力匹配原则和原型叶片模型的弦长,对浮式风机叶片模型的弦长进行重建。遗传算法被用于优化控制策略(在不同风速下的桨距角和转子转速),以最小化浮式风机模型的推力和扭矩与期望推力和扭矩之间的差异。该方法被应用于不同速度尺度比下的 DTU 10MW 和 IEA 15MW 风力发电机的叶片模型重建,展示了其在不同风机类型中的适用性。结果表明,在调整控制策略后,浮式风机模型的推力和扭矩与期望值的误差大部分在 5%以内。 (3)针对搭载新型混合式浮式基础(半潜式+立柱式)的浮式风机,制作了 1:50 的试验模型,进行水动力模型试验,研究了新型浮式风机的水动力性能。首先进行了自由衰减试验和 RAO 试验、系泊系统静水刚度试验,验证了模型的准确性。然后进行了单独风、单独浪、风浪联合的水动力试验,验证了浮式风机的水动力性能,并将试验结果与数值分析结果进行了对比。

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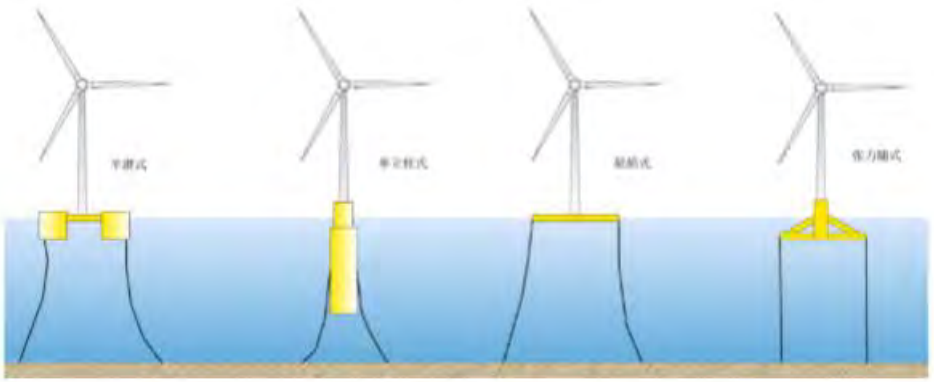

图1.1 不同浮式风机及其基础类型[10]

NOKOV 度量动作捕捉在研究中的应用摘录

5.2.5 六自由度光学动作捕捉系统
动作捕捉系统主要由动作捕捉镜头和光学 Marker 组成。动作捕捉镜头作为系统核心组件，承担着对研究对象动态行为的量化记录功能。其光学模组经特殊工艺优化，可将三维空间坐标信息在感光芯片端完成预处理运算。这种前端数据处理机制有效提升了动作捕捉系统的鲁棒性，通过硬件算法协同优化，在保证亚毫米级精度，为后续运动学分析提供了稳定可靠的数据流基础。
本次试验中采用了四台 NOKOV 度量品牌的 Mars4H 镜头。该镜头像素 4MP，分辨率为 2048\2048，延迟 5.2ms，如图 5.21 所示。通过动作捕捉系统，直接获取浮式风机六自由度(6Dof)运动数据。
光学捕捉镜头需要配合光学 Marker 点才能使用。四个不共面的 Marker 点可以构成一个刚体，为了防止部分 Marker 点被遮挡造成试验数据有噪点，本试验选用了 7 个 Marker 点。Marker 点示意图如图 5.22 所示。

引用格式 刘龙辉.浮式风机水池试验及叶片模型重构方法研究[D].哈尔滨工程大学,2025.DOI:10.27060/d.cnki.ghbcu.2025.000239.

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基于改进 YOLOv5n 的仿生海豚目标识别与跟踪方法

关键词

仿生机器海豚;水下目标识别;YOLOv5n 检测网络;目标跟踪;

摘要

针对仿生机器海豚水下识别与跟踪任务要求低延迟与高实时性等特点，提出一种基于改进 YOLOv5n 的仿生海豚目标识别与跟踪方法。该方法使用轻量化网络 GhostNet 替代原 YOLOv5n 的主干网络，从而减少算法网络结构的浮点运算次数，提升仿生海豚水下目标检测与识别的实时性与可靠性，并最终与 DeepSORT 跟踪算法融合，完成对识别目标的跟踪任务。仿真与实验结果表明：改进后的算法更加轻量化，且识别效率高，跟踪误差小，验证了算法在仿生海豚水下目标识别与跟踪任务中的可行性与高效性。

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(a) 测试平台水池 (b) 仿生机器海豚 (c) 动捕相机 (d) 标定系统

图 4 仿生机器海豚实验装置

NOKOV 度量动作捕捉在研究中的应用摘录

3 实验验证与分析
3.1 实验环境搭建
本文所选择的实验水池大小为 6.0mx4.0mx1.5 m,并搭建了基于 NOKOV 红外动捕相机的在线跟踪系统,能够实时精确地获取到机器海豚的游动姿态及轨迹等运动参数。测试平台水池,组装好的仿生机器海豚与其他实验设备如图 4 所示。
本文实验的在线跟踪系统主要由 8 台动捕相机、Mark 点、静态标定板、动态标定杆以及计算机组成。动捕相机通过网络交换机与计算机相连接以传输数据,Mark 点粘附在机器海豚上,以便动捕相机能够捕捉 Mark 点的运动状态及轨迹。静态标定板和动态标定杆同样粘附 Mak 点，主要用来确定在线跟踪系统的全局坐标系,以获取 Mak 点的坐标位置。动捕相机位置识别效果如图 5 所示。

引用格式 曾广娟,陈宏,陈昭阳,等.基于改进 YOLOv5n 的仿生海豚目标识别与跟踪方法[J].传感器与微系统,2025,44(08):93-96+100.DOI:10.13873/J.1000-9787(2025)08-0093-04.

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基于可变前向距离 LOS 导航法的仿生海豚路径跟踪研究

关键词

仿生机器海豚;视线导航法;可变前向距离;路径跟踪;

摘要

针对仿生机器海豚的水下路径跟踪控制问题，研究了一种基于可变前向距离的视线(LOS)追踪路径跟踪算法；算法采用可变前向距离代替传统 LOS 导航算法的固定前向距离，创新设计了一种反正切函数，利用载体当前状态与期望路径状态对前向距离进行实时计算与修正，使仿生机器海豚有效克服传统 LOS 导航算法的过冲与延迟收敛问题，并结合仿生机器海豚的水下运动能耗特点，有效降低运动能耗；最终通过仿真与实物实验，验证了算法的可行性、准确性，智能性与优越性。

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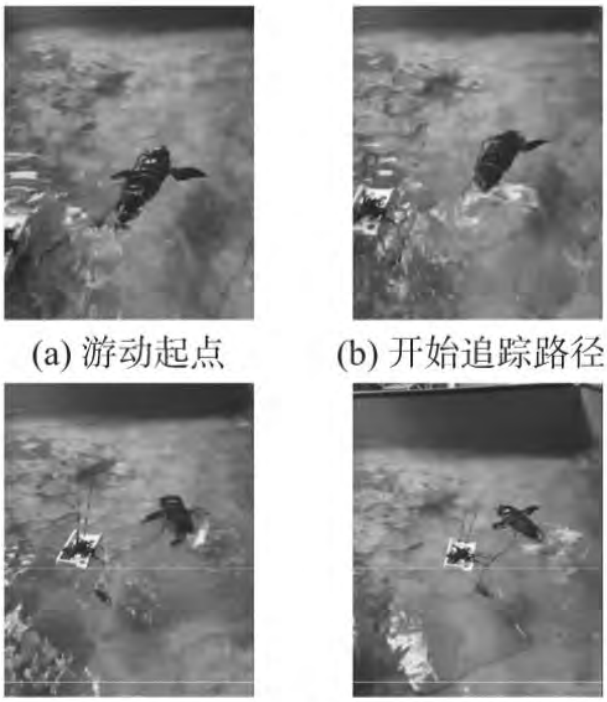

(a) 游动起点　(b) 开始追踪路径

(c) 追踪中　(d) 追踪至期望状态

图 7　仿生海豚下潜游行状态

NOKOV 度量动作捕捉在研究中的应用摘录

> *3.2 仿生海豚水下实验测试*
> *为了验证算法在机器海豚上的真实有效性，进行水下实验验证。实验水池大小为 6.0mx4.0mx1.5m,在海豚下水实验之前搭建完成实验装置,搭建了基于 NOKOV 红外动捕相机的在线追踪系统,能够实时精确地获取到海豚的游动姿态及轨迹等运动参数。测试平台水池与组装好的仿生机器海豚如图 6 所示。*

引用格式 陈昭阳,陈宏,曾广娟,等.基于可变前向距离 LOS 导航法的仿生海豚路径跟踪研究[J].传感器与微系统,2025,44(12):33-37.DOI:10.13873/J.1000-9787(2025)12-0033-05.

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基于摩擦纳米发电的仿鱼尾本体感知技术研究

关键词

摩擦纳米发电机；自驱动传感；本体感知；柔性仿生

摘要

水下信息感知技术是水下机器人高效作业的重要支撑，传统的水下信息感知虽然能够完成特定的任务，但仍存在一些问题，例如，水下声呐在复杂海底环境中容易受到干扰，水下视觉在近岸障碍物众多、环境浑浊时，识别精准度较低。本文从鱼类的水下本体感知中汲取灵感，利用摩擦纳米发电机在低激励下产生高电压的特性，设计了基于摩擦纳米发电的仿鱼尾本体感知器件（Fishtail-shaped Proprioceptive Sensing Prototype， FPSP）并进行了系统研究。通过分析器件中多感知单元的电信号解算出水下机器人在水下运动的姿态，以适应更为复杂和多变的水下环境，让水下机器人具备更高的智能化和自适应性能。本文的研究工作包括以下几个方面：

（1）FPSP 构型设计与动力学特性分析。采用稳流场模型、器件构型表面受力模型与器件弹性力学模型，建立本体感知器件的动力学模型。进一步，柔性仿生构型产生形变，进而引起内部的摩擦纳米发电机产生自驱动信号，搭建本体自驱动感知器件动力学与电信号输出性能协同测试系统。最后，研究构型参数和材料性质等因素对器件动力学响应特性的影响规律，并用 ANSYS 对本体感知器件进行动力学仿真分析，COMSOL 进行静电仿真验证，以探索具有良好响应特性的本体感知器件设计方案。

（2）稳定流场下的 FPSP 信号输出性能研究。使用水下三维动态捕获水池、信号放大模块、USB2AD7606 采样板以及采样板上位机可视化程序搭建感知测试平台。结合柔性仿生器件的动力学响应特性，研究不同摆动参数（摆频、摆幅）对本体感知器件信号输出性能的影响规律。研究不同稳流条件下对本体感知器件信号输出性能的影响规律，优化提升本体感知器件的适应性。最后分析 FPSP 感知单元的信噪比和耐久性证明 FPSP 具有较强的稳定性。

（3）仿生自驱动本体感知器件构建与功能验证。将机器鱼与 FPSP 进行系统集成，对 FPSP 感知单元数据集进行预处理，使用一种基于 CNN-LSTM 神经网络本体感知算法用于辨识机器鱼尾姿态特征，建立复杂流场条件下的机器鱼尾姿态与感知单元信号的映射模型，水池中 FPSP 训练的平均均方根误差约为 0.0412，损失函数值约为 0.0008。对训练好的神经网络模型进行验证，预测机器鱼尾在水下的运动姿态，完成水下三维空间环境的评估和姿态调整等任务。进一步，在实验水池中对 FPSP 进行实时控制验证，在水下扰动源作用下机器鱼能够自适应的调整姿态，减少扰动对 FPSP 信号输出的影响。最后，将 FPSP 安装在水下机器人上进行局部位置预测，验证感知器件对运动姿态获取及外部流场的感知能力。

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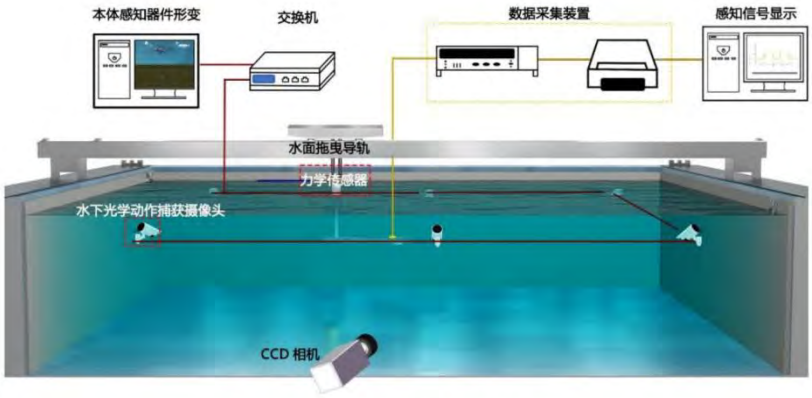

图 4. 5　动作捕捉区域

Figure 4. 5　Motion capture area

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> *实验装置包括多功能水池，用来获取位置数据的运动捕捉系统，如图 4.5 和图 4.6 所示。采用 6 个 Nokov Mars4HUW 相机组成水面运动测量系统，捕捉机器鱼尾姿态变化。POE 交换机将多个数字动作捕捉镜头捕捉到的位置信息同步并综合，发送给系统处理终端。*

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基于姿态仪误差修正的绞车升沉补偿系统控制研究

关键词

升沉误差修正;绞车型升沉补偿系统;姿态仪;支持向量机;

摘要

浮式作业平台运动的测量精度是影响浮式作业升沉补偿系统补偿精度的主要因素之一。由于海上没有固定的参考系,检测浮式作业平台的运动大多采用基于惯性测量的姿态仪,但目前主流姿态仪的升沉检测精度为 50 mm 或幅值 5%(取较大值),导致升沉补偿系统难以实现 95%的补偿率。对姿态仪的误差进行修正,提高其测量精度,是提高升沉补偿系统补偿精度的有效措施。本文以绞车型升沉补偿系统为对象,对姿态仪误差修正方法及其对补偿精度的改善效果开展研究。主要研究内容包括: (1)姿态仪升沉误差机理分析与动态标定系统设计。针对传统静态标定无法表征运动耦合误差的问题,解析加速度计零偏、陀螺漂移与安装偏差的复合作用机理,构建六自由度运动平台驱动的动态标定系统。开发基于 MFC 架构的标定软件,实现动捕数据与姿态仪输出的时空同步采集,建立包含幅值、频率参数的升沉误差数据集,ANOVA 分析表明幅频参数对误差影响显著。(2)基于 BO-SVM 分类的误差修正方法研究。首先,阐述了 SVM 的工作原理、BO 原理,并介绍了 LIBSVM 工具箱;然后,利用 LIBSVM 工具箱通过 SVM 算法建立了多误差分类模型,采用 BO 算法对建立的多误差 SVM 模型参数进行全局寻优;最后,设计了基于多模型融合的误差修正方案,通过状态转移逻辑实现误差的平滑修正。经过离线验证和物理实验验证发现,进行修正后可将 30 mm 幅值,0.1、0.12 和 0.14 Hz 工况下的平均均方根(RMSE)降低 37.6%。 (3)基于 BO-BP 拟合的误差修正方法研究。介绍了 BP 神经网络原理,并运用其原理搭建了误差拟合模型,设计了分层贝叶斯优化策略,突破传统 BP 网络参数寻优局部极值限制,进一步提升模型的拟合性能。离线验证与在线实验结果表明该方法较 BO-SVM 进一步降低 RMSE 至 45.9%。 (4)姿态仪误差修正对升沉补偿精度的改善效果研究。阐述了系统的组成和原理,并根据其原理搭建了基于姿态仪误差修正的绞车型升沉补偿系统的 AMESim-Simulink 联合仿真平台与物理模拟实验系统。仿真与实验结果表明,对姿态仪的误差进行修正后,可以有效的提升补偿系统的精度和补偿率。 研究结果表明,本研究提出的自主式误差修正方法,无需外部数据,通过运用 BO-SVM 修正后的姿态仪升沉信号作为控制信号,对比运用未修正的升沉信号,使得升沉补偿的精度平均提升了 21.0%;而运用 BO-BP 修正的信号,对比未修正信号,使得补偿精度平均提升了 41.2%;且平均补偿率分别提升了 8.5%和 10.8%。可见,对比传统的多传感器融合修正和单一误差源的溯源修正,该方法具有创新性和实际应用价值。

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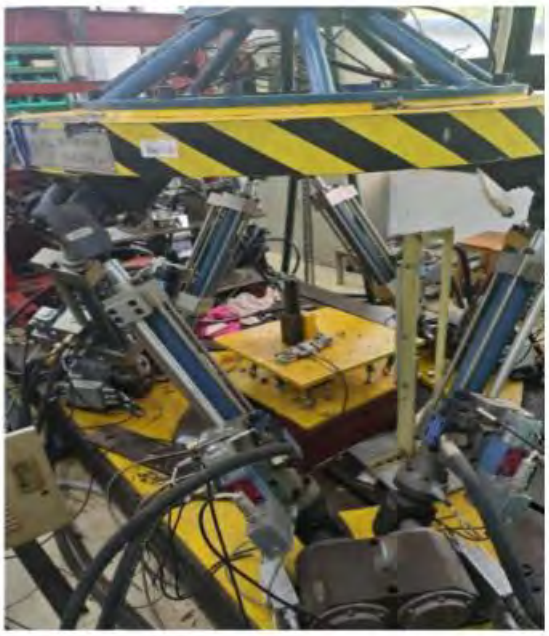

(a) 六自由度运动平台

(b) 姿态仪

(c) 动态捕捉系统摄像头

图 2-7 姿态仪输出标定系统

NOKOV 度量动作捕捉在研究中的应用摘录

1.实验平台搭建
(1)硬件配置
硬件主要包括姿态仪、动态捕捉系统、上位机和六自由度运动平台组成。姿态仪型号为 Ekinox-A，采样频率 200 Hz；动态捕捉系统为 NOKOV 度量动作捕捉系统，采样频率 60 Hz，精度 0.5 mm；上位机是研华工控机，CPU 为 i5-1240p，内存为 16GB RAM；六自由度运动平台由哈尔滨工业大学研制，位置误差 1 mm。

引用格式 全永贵.基于姿态仪误差修正的绞车升沉补偿系统控制研究[D].广东工业大学,2025.DOI:10.27029/d.cnki.ggdgu.2025.000972.

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具有多运动模式的水下仿生软体机器人创新设计与自适应控制策略研究

关键词

水下仿生软体机器人；结构优化；自适应路径规划；自适应滑模控制

摘要

水下软体机器人具备较好的柔顺性、抗冲击能力、环境适应性和生物亲和性，在海洋生态环境检测及水底生物多样性探测等领域具有重要的研究意义和应用潜力。水下探测任务面临着水流扰动以及狭窄崎岖水底环境等挑战，需要水下软体机器人具备多种运动模式、高效的游动能力、高质量的路径导航和精准的轨迹跟踪控制等方面性能。然而，软体材料的非线性特性和水下未知环境的干扰使得原本就较复杂的探测过程变得更加复杂和难以控制。因此，本文的研究重点是如何在狭窄崎岖的水底环境中，高效且精准地完成水下软体机器人的探测任务。本文的主要工作如下：设计了具有多模式且可控过渡的水下仿生软体机器人，并对其陆地步行和水面游动的运动性能进行了验证。本文依据口虾蛄生物的运动特点，基于介电弹性体驱动材料设计了一种水下仿生软体机器人，其不仅具有狭窄空间前进与后退、从陆地步行过渡到水面、从水面潜水过渡到水底、从水底爬行过渡到陆地等循环可控运动模式，而且具有较高的运动速度、自适应性和灵活性，极大地提升了狭窄崎岖水底环境中探测任务的可行性与完成度。

为了解决水下仿生软体机器人游动过程中运动效率低及适应性差的难题，本文将结合ＰＩＶ实验与流体有限元仿真方法，在突变激励下对水下仿生软体机器人进行优化设计，开发出运动效率和适应性最佳的几何结构。以此为基础，构建具有不同结构、不同转速和不同柔性角的水下仿生软体机器人水动力学模型，以精准表达突变激励下不同结构与柔性角度的动态特性。

为了应对水下仿生软体机器人在狭窄崎岖水底环境下从起始点到目标点之间的路径质量不稳定、运动成本高等挑战，开发了一种具有扩展步长调整方案、障碍环境判断模型和优化后处理算法的自适应RRT－Ｃｏｎｎｅｃｔ规划策略，能够快速、高效地规划出穿越狭窄崎岖水底环境的高质量路径，降低水下仿生软体机器人在探测任务中的运动成本。

针对水下仿生软体机器人在狭窄崎岖水底环境下轨迹跟踪控制过程中受到的较大不确定性问题，基于考虑非线性迟滞、蠕变性以及与速率相关迟滞行为的动力学模型，提出了一种包含非线性干扰观测器、自适应算法、饱和函数趋近律、分数阶非奇异终端滑模面在内的自适应分数阶非奇异终端滑模控制器。该控制器有效提高了应对较大参数不确定性和外界干扰的能力，增强了水下仿生软体机器人控制系统在探测任务中的控制精度和鲁棒性。

本文结合水下仿生软体机器人的路径规划方法和轨迹跟踪控制方法，开展了执行水下目标探索任务的综合实验，验证了本文软体机器人整体自适应策略的可行性，证明了水下仿生软体机器人在所提自适应策略加持下能够精准地完成水下目标探测任务。

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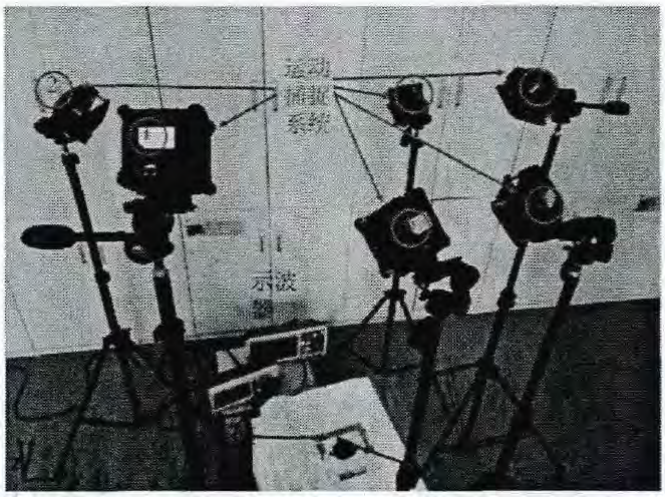

图 6-5 薄膜的位移运动变化捕捉实验

NOKOV 度量动作捕捉在研究中的应用摘录

如图 6-5 所示，运动捕捉系统（NOKOV-Mars 1.3H）利用 6 个摄像头对薄膜或者软体机器人进行三维运动捕捉。摄像头的分辨率为 130 万像素，最大频率为 240Hz，视场角为 57°×44°，精度为±0.2mm. 在运动捕捉系统设备下可以采集到薄膜三维运动加速度、速度和位移的数据。

引用格式 李庆中.具有多运动模式的水下仿生软体机器人创新设计与自适应控制策略研究[D].山东大学,2023.DOI:10.27272/d.cnki.gshdu.2023.007442.

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螺旋桨式全驱动小型水下机器人抗扰动稳定控制

关键词

水下机器人；抗干扰；强化学习；迁移学习

摘要

十四五规划要求进一步发展战略性新兴海洋装备产业，提高海洋资源开发水平。水下机器人作为海洋装备的重要组成部分，可以完成多种水下任务。但是在工作过程中，机器人会面临各种系统不确定性及外部干扰问题，其控制等的稳定性和精度通常会受到影响。提高水下机器人系统的可靠性是扩大海洋装备实际应用的范围的关键，因此需要一种故障安全且适用于扰动环境的自主水下机器人系统及一套通用的控制算法。本课题主要研究了机器人在工作过程中面临的三种不确定性及扰动问题：定位不确定性、机器人动态模型不确定性和动态水域水动力干扰。针对上述不确定性及干扰问题，研究者们已提出了许多扰动抑制控制算法，但现有的算法或因控制饱和或低能抗强度较小的干扰或依赖精度足够的动态模型，这些都导致现有算法在水下机器人上抗干扰能力有限。随着人工智能技术的发展，无模型强化学习可以在难以精确系统建模时通过与系统和环境反复交互学习最优控制率。强化学习通过有效引导试错的方式在未知的模型中找到最优的控制策略，并能够很好地适应系统中的不确定性和噪声。但过大的扰动和不确定性使得现有学习方法获得的控制率具有鲁棒性但位置追踪误差较大。

本课题通过对真实受扰动水下机器人的分析，建立了相应的仿真环境，研发基于强化学习的扰动抑制算法。针对水下机器人的定位不确定问题，本课题首先利用扩展卡尔曼滤波对非同步传感器信息进行数据融合，获得了准确的机器人姿态信息，然后在传统的 PID 控制器的基础上，研究了强化学习控制器针对非同步传感器输入时的输入空间选择问题，提出了基于卡尔曼滤波的强化学习方法并在历史窗口的端到端的强化学习方法。接着，针对真实环境与仿真环境下机器人动力学模型不匹配以及可能出现的螺旋桨驱动器失效问题，本课题探究了域随机化的强化学习方法并提出了基于动态模型对齐的迁移强化学习方法，将在仿真环境中训练获得的控制策略迁移到实物机器人上，并在仿真环境中与实物环境中进行了实验验证，取得了不错的控制策略迁移效果。针对机器人在动态水域工作时面临的不同强度水流干扰问题，本课题提出了基于运动学仿真的抗扰动控制算法，提出了利用数据驱动的方案得到了水动力干扰的估计器，机器人动力学模型估计器和逆动力学模型估计器。这三种估计器依赖机器人的运动状态和控制信息可以实时在线估计受扰动机的机器人逆动力学模型，并通过运动学模仿，将无干扰环境下学习获得的控制策略迁移到有干扰环境的机器人上，输出干扰环境下的控制策略，仿真结果表明该策略可以很好的抵抗水流干扰。综上所述，本课题开展了针对水下机器人不确定性及外部扰动的强化学习研究，通过仿真与水池实验初步验证了所提出的动力学模型学习及策略迁移方法，为解决更具挑战的水下机器人控制问题提供了可行思路。

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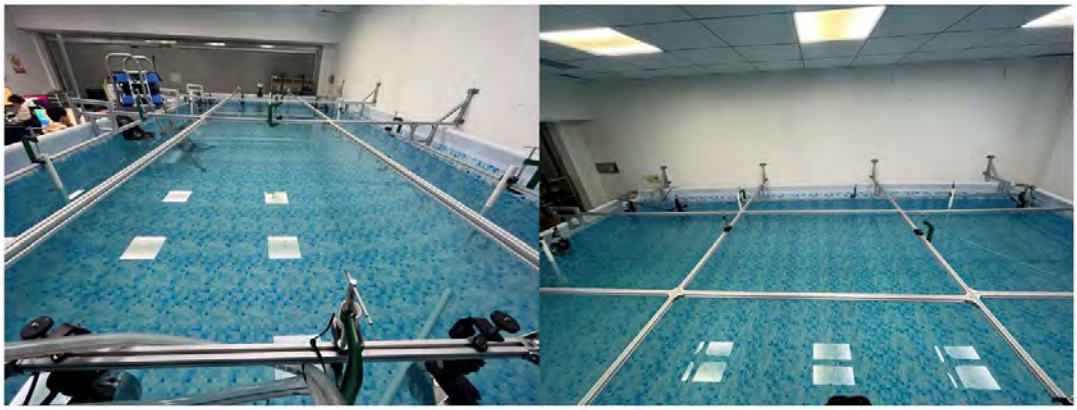

图 6-1 实验室搭建的水池环境

NOKOV 度量动作捕捉在研究中的应用摘录

在对水下机器人进行精密控制时，需要实时获取机器人的相对准确的位姿信息。而机器人现有的机载传感器的精度无法满足要求，因此我们在水池边缘安装了一套基于光学定位的动态捕捉系统。这套系统配备了 12 个水下发光镜头，机器人上安装了 4 个反光球（反光球通过 3D 打印零件与机器人连接），如图 6-2。这些镜头通过感应机器人反光球的位置完成对机器人的位置估计。该系统定位系统精度较高，可以最高以 100Hz 的频率获取机器人的位置、角度和线速度信息。

引用格式 程凯.螺旋桨式全驱动小型水下机器人抗扰动稳定控制[D].哈尔滨工业大学，2023.DOI：10.27061/d.cnki.ghgdu.2023.005085.

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万吨级上部组块浮托安装系统动力响应试验研究

关键词

浮托安装作业;对接分析;荷载连续转移;桩腿耦合装置;动力响应特征;

摘要

浮托安装荷载转移过程，由于作业驳船吃水的连续变化、舱室的持续压载以及上部组块与缓冲装置接触状态的间歇性转变，导致浮托安装系统自身的动力特性及所受的环境荷载呈现出显著的非稳态特性，传统基于稳态假设的模拟方法难以准确预测荷载转移过程中浮托安装系统的动力响应。本文以渤海海域最大导管架平台 KENLI 10-2 CEPC 平台为例，开展了浮托安装荷载转移过程连续模拟模型试验，探究了不同环境条件下浮托安装系统中作业驳船、上部组块的运动响应及缓冲装置的碰撞力，并与稳态假设条件下的数值模拟结果进行对比。研究结果表明，模型试验测量得到的驳船及上部组块垂荡运动响应幅值较同等条件下数值模拟结果分别高出约 1.6%和 6.7%，而模型试验测量得到的桩腿对接缓冲装置 LMU (Leg Mating Unit) 和甲板支撑结构 DSU (Deck Support Unit) 碰撞力较同等条件下数值模拟结果分别高出约 10.76%和 13.38%。而对接缓冲装置的响应最大值均出现在荷载连续转移终止后的瞬间，荷载转移连续模拟模型试验成功的捕捉到了传统基于问题假设的模拟方法无法捕捉的瞬态碰撞现象。

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图 8 浮托安装水池模型试验

NOKOV 度量动作捕捉在研究中的应用摘录

3.4 浮托安装系统运动响应 RAO
将浮托驳船与上部组块进行固定连接，并放置在水池中央，利用水平系缆进行定位，利用 NOKOV 度量光学三维动作捕捉设备对其运动响应进行测量，利用测量得到的规则波浪幅值对测量得到的浮托安装系统运动响应幅值进行归一化处理，即可得到浮托安装系统运动响应幅值算子 RAO（Response Amplitude Operator）。0°荷载和 180°荷载作用下模型试验结果与数值结果分别如图 12 和 13 所示。

引用格式 魏宇豪,焦其超,刘旭,等.万吨级上部组块浮托安装系统动力响应试验研究[J/OL].海洋工程,1-14[2025-11-10].https://link.cnki.net/urlid/32.1423.P.20251017.1546.004.

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胸鳍/尾鳍协同推进的机器海豚动力学建模与仿真

关键词

机器海豚；协同推进；动力学模型；胸鳍/尾鳍；数值仿真

摘要

动力学模型是机器海豚研究的一个重点和难点。基于胸鳍/尾鳍协同推进模式,采用"叶片单元法"建立 2 自由度胸鳍动力学模型,根据伯努利原理和大展弦比机翼平衡理论提出尾鳍动力学模型。通过 MATLAB 进行数值仿真,获取胸鳍、尾鳍的运动规律和不同模式下的游动速度；进一步分析机器海豚的游动模式和运动参数对直游性能的影响,为机器海豚的设计提供理论依据。该研究有助于进一步认识和研究海豚的运动机理,从而提高机器海豚的游动性能。

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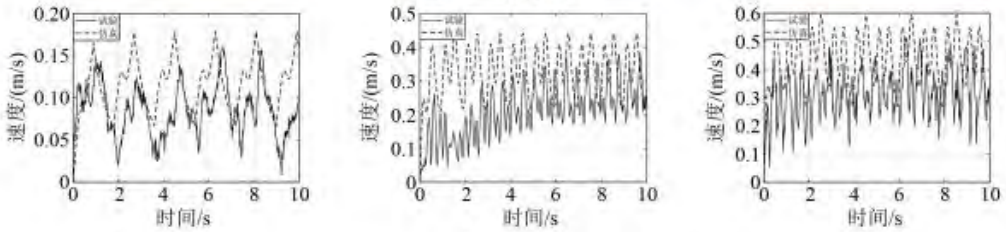
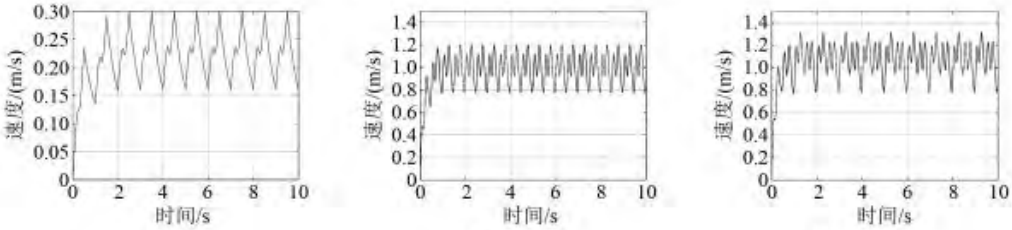
(a) 泳池　(b) 数据采集系统　(c) 粘附 Mark 点的机器海豚

图 8　试验设备



(a) 模式 1　(b) 模式 2　(c) 模式 3

图 9　不同推进模式下的仿真与试验



(a) 模式 1　(b) 模式 2　(c) 模式 3

图 10　不同推进模式下的仿真直游速度

NOKOV 度量动作捕捉在研究中的应用摘录

采用相同的运动参数研究不同推进模式下，机器海豚的游动性能差异。首先通过试验对提出的动力学模型进行验证，试验环境见图 8，采用大小为 640cm×407cm×150cm 的泳池和 Nokov 动捕相机进行游动试验。动捕相机采用双绞线，通过网络交换机与计算机相连接，以传输数据和供电，同时能捕捉粘附在机器海豚上的 Mark 点的运动状态，从而获取机器海豚的游动姿态和运动参数。试验与仿真对比见图 9。在不同推进模式下对机器海豚进行速度仿真，结果见图 10。

引用格式　杨忠华，巩伟杰.胸鳍/尾鳍协同推进的机器海豚动力学建模与仿真[J].船舶工程，2021,43（09）：140-145+151.DOI：10.13788/j.cnki.cbgc.2021.09.25.

链接

https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C44YLTlOAiTRKibYlV5Vjs7iy_Rpms2pqwbFRRUtoUImHW2_jYd-ynSsFVOuybf80t1aVy93n2nrBNxLqH46jFJe&uniplatform=NZKPT

智能集群仿真与实验验证研究综述

关键词

智能集群；仿真与实验；现状与发展

摘要

本文围绕智能集群仿真与实验验证系统内涵、现有各类集群验证系统项目、集群仿真验证系统趋势分析三个方面进行综述。首先介绍了智能集群及其验证系统的概念及背景,然后从陆、空两方面梳理总结现有的智能集群仿真与实验典型项目,最后,基于已有的成熟的验证系统和仿真技术进行归纳分析,对智能集群验证系统未来发展趋势提出合理建议和展望。

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NOKOV 度量动作捕捉在研究中的应用摘录

ACL 还设计可测量的用于增强现实环境的网络-物理系统用于集群验证 ，系统包括运动捕捉技术、车载传感器和投影仪等，是旨在将室内实验室转变为室外环境的受控模拟平台。北京理工大学、中科院自动化研究所、同济大学建筑系 基于 NOKOV（度量）光学动作捕捉系统环境，提高智能体系统鲁棒性。格拉茨技术大学计算机图形学与视觉研究所成立专门的室内验证场一 dronespace，配备了高精度运动跟踪系统，允许灵活的视觉传感器设置取 GPS 进行定位，可跟踪准确姿态测量值，用于验证室内机器人搜寻与援助、避障、室内制图、目标识别与跟随等。

引用格式 李嘉轩,杨雪榕,杨雅君,杨起帆. 智能集群仿真与实验验证研究综述[C]//. 第 22 届中国系统仿真技术及其应用学术年会（CCSSTA22nd 2021）论文集.,2021:141-149.DOI:10.26914/c.cnkihy.2021.059226.

链接

https://cpfd.cnki.com.cn/Article/CPFDTOTAL-XTFZ202110001027.htm

万吨级上部组块浮托安装就位等待阶段动力响应特性

关键词

上部组块;浮托作业;就位等待;耦合分析;动力特性;

摘要

以渤海海域最大导管架平台垦利 10-2CEPC 中心平台为研究对象，建立浮托安装系统整体耦合动力分析数值模型，利用模型试验结果验证数值模型的有效性，基于数值模型探究环境载荷方向、波浪参数等对浮托安装系统就位等待阶段动力响应的影响规律。结果表明，数值模拟与模型试验得到的浮托安装系统动力响应统计结果吻合较好，在顺向载荷作用下浮托安装系统的动力响应幅值较小，在横向载荷作用下浮托安装系统的动力响应幅值较大，但仍可满足浮托作业进船过程对系统动力响应的要求。

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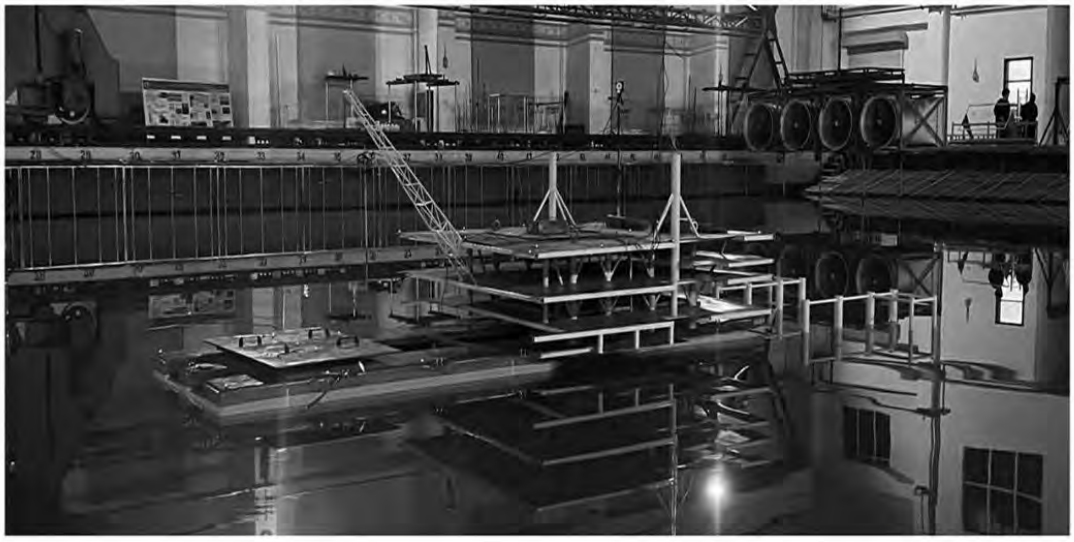

图 9　浮托安装系统就位等待阶段模型试验布置

NOKOV 度量动作捕捉在研究中的应用摘录

> *3．3 运动响应传递函数校验\n 为了进一步验证模型试验中作业驳船与上部组\n 块加工和调整的精度，利用水池设备生成一系列周\n 期不同的规 则 波 浪，采 用 NOKOV 度 量 光 学 三 维\n 动作捕捉 设 备 测 量 浮 托 安 装 系 统 的 运 动 响 应，进\n 一步 得 到 浮 托 安 装 系 统 的 运 动 响 应 幅 值算子\n（ResponseAmplitudeOperator，RAO，即 运 动 响\n 应传递函数），并与相同条件下的数值结果进行对\n 比，结果如图 7 和 8 所示。*

引用格式 沈亮,马晋雄,李响,等.万吨级上部组块浮托安装就位等待阶段动力响应特性[J].中国海洋平台,2026,41(3):76-85.

链接

https://kns.cnki.net/kcms2/article/abstract?v=sFGZ-GfRoEWin7puq8Zu61AyNDsAeintbkOg4FtL8mnuxaiSIU5pCSMq83zqxBuNqbY-Nn1xLubfIJ7-kakFrUuf43Xjofv1OJC9XDuNfwm5SyfHhyEU2zfFO-hkens1bqMi0n_yhmWkYNayly7-o4mqVgjqNbv6u8f6UtDyDU08FW8BP2aPBg==&uniplatform=NZKPT&language=CHS

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VI. Soft Robot

A Modular Soft Pipe-Climbing Robot With High Maneuverability

Keywords

Maneuverability, modular design, pipe climbing robot, soft robotics.

Abstract

Pipeline is widely deployed in infrastructures, which raises a great demand of pipe-climbing robots to pro vide pipe-inside inspecting and platform delivery. Soft pipe climbing robots (SPRs) are intrinsically flexible and able to operate within complex, narrow and curving pipelines more effectively than their rigid counterparts. In the state of the art, the existing SPRs have demonstrated their performances in fixed-diameter pipes that are placed in static fluid environments, which however does not show their full potential. In this article, we propose a modular design methodology for SPRs that are expected to operate inside complex pipelines. The robot's torso is composed of three PSAs in parallel, which can realize axial elongation as well as omnidirectional bending with pressurized air. The PSA-based tentacles will elongate after inflation to contact and hold the pipe wall using their silicone pads. Further more, the slim tentacles and compact torso results in quite small cross-sectional occupation ratio and subsequently low windward resistance from the liquid in the pipeline, which ensures the robot's high passivity in fluid. The pro posed robot can adapt to and work in diverse pipelines with complex fluid conditions, such as horizontal and vertical straight, as well as curved pipes with varying diameters, with and without loads, in still and dynamic water flows. In addition, the robot, whose weight is 50 g, can achieve a fast speed of climbing (up to 15.0 mm/s in open air) and high load-carrying ability (up to 1500 g) due to the quick response of the tentacles and large elongation ratio of its body. The experimental results have proved the high maneuverability of the developed SPR.

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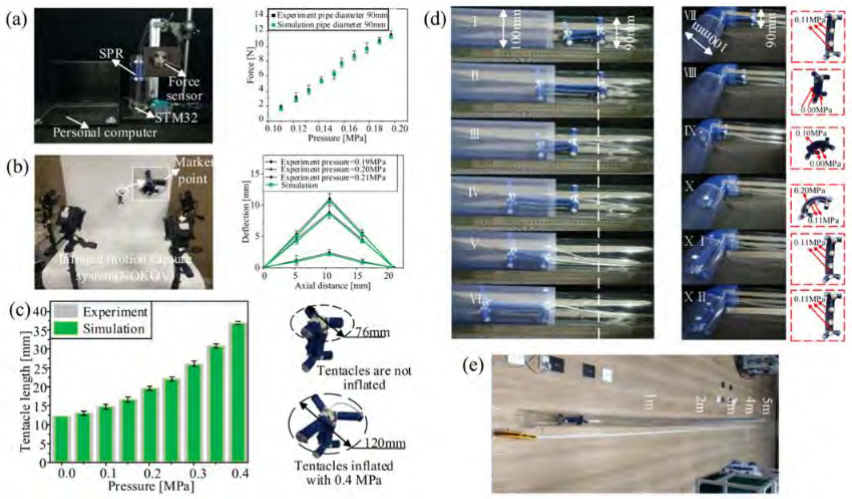

Fig. 3. Motion performance of SPR. (a) Test and simulation of tentacle force. (b) Test and simulation of tentacle bending. (c) Test and simulation of tentacle extending. (d) Crawling in pipes with different diameters and corners. (e) Crawling in 5 m long pipe.

How NOKOV Contributes to the Research

To investigate the buckling behavior of tentacles, we tested the deflection profile when the PSAs were pressurized.Three reflective markers were pasted on one of the tentacles,which were monitored by the NOKOV motion capture system.

Citation W. Wang et al., "A Modular Soft Pipe-Climbing Robot With High Maneuverability," in IEEE/ASME Transactions on Mechatronics, doi: 10.1109/TMECH.2024.3385506.

Link https://ieeexplore.ieee.org/document/10509550

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A Novel Elbow-Inspired Cable-Driven Tensegrity Joint: Bionic Design, Coupled Kinematics, and Load Performance

Keywords

tensegrity robot joint, bio-inspired design, cable-driven mechanisms, bionic structure, compliant mechanisms and robots

Abstract

Tensegrity-based robot joint offers mechanical compliance under external impact and in man-robot interaction. So its practical bionic design has become a research hotspot. A variety of tensegrity-based flexible joints have been proposed and verified, but the research is not in-depth enough on control and motion modeling, transmission characteristics, and load performance analysis for robot joints with coupled driving cables and tensegrity structure. Based on the current situation, an elbow-inspired rotary joint is proposed following human anatomy. With the help of tensegrity node balance, the inherent relationships between the joint's rotation and translation and between the driving cables" tension and the joint's rotation are derived. The load performance of the joint is also explored, and the end load is calculated from the deviation between cables' tension of a no-load condition. A prototype and an antagonistic cable driver with tension sensors are designed and manufactured to verify the proposed model, and the experimental results are well in agreement with the theoretical prediction. In the future, the model and the method proposed will be applied to bionic joints with similar structures.

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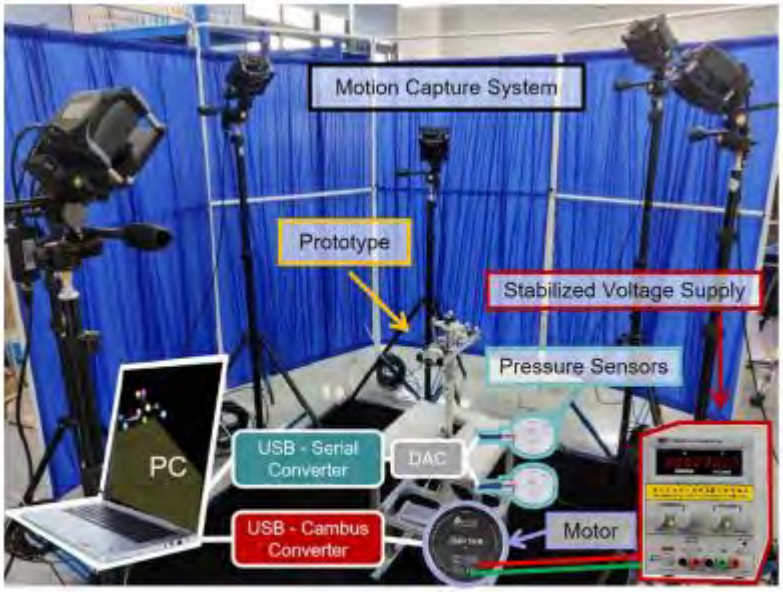

Fig. 6 The motion capture system

How NOKOV Contributes to the Research

In this section, the experiments on our prototype and simulations configured according to actual parameters are conducted for comparison purposes. The configuration parameters are shown in Table 2. The motion capture system is shown in Fig. 6: it consists of six NOKOV (Beijing, China) branded lenses with an accuracy of 0.2 mm and data acquisition up to 60 Hz; the black absorbent flannelette laid on the floor and the surrounding isolation curtain can reduce environmental disturbances. The lower part of Fig. 6 shows the control connection of the prototype: the PC communicates with the motor through the USB module to issue movement commands.

Citation Xie X, Xiong D, Li Z, et al. A Novel Elbow-Inspired Cable-Driven Tensegrity Joint: Bionic Design, Coupled Kinematics, and Load Performance[J]. Journal of Mechanisms and Robotics, 2024, 16(10): 101003.

Link

https://asmedigitalcollection.asme.org/mechanismsrobotics/article/16/10/101003/1193913/A-Novel-Elbow-Inspired-Cable-Driven-Tensegrity?searchresult=1

A novel inverse kinematics and shape reconstruction method for continuum robots

Keywords

Continuum robots, Inverse kinematics, Shape reconstruction

Abstract

Purpose:Continuum robots offer unique advantages in various specialized environments, particularly in confined or hard-to-reach spaces. Inverse kinematics and real-time shape estimation constitute crucial aspects of closed-loop control for continuum robots, presenting challenging problems. This paper aims to present an inverse kinematics and shape reconstruction method, which relies solely on the knowledge of base and end positions and orientations.Design/methodology/approach:Based on the constant curvature assumption, continuum robots are regarded as spatial curves composed of circular arcs. Using geometric relationships, the mathematical relationships between the arc chords, points on the bisecting plane and the coordinate axes are established. On this basis, the analytical solution of the inverse kinematics of the continuum robots is derived. Using the positions and orientations of the base and end of the continuum robots, the Levenberg–Marquardt algorithm is used to solve the positions of the cubic Bezier curves, and a new method of spatial shape reconstruction of continuum robots is proposed.Findings:The inverse kinematics and spatial shape reconstruction simulation of the continuum robot are carried out, and the spatial shape measurement experimental platform for the continuum robot is constructed to compare the measured and reconstructed spatial shapes. The results show that the maximum relative error between the actual shape and the reconstructed shape of the continuum robot is 2.08%, which verifies the inverse kinematics and shape reconstruction model. Additionally, when the bending angle of a single bending section of the continuum robot is less than 135°, the shape reconstruction accuracy is higher.Originality/value:The proposed inverse kinematics solution method avoids iterative solving, and the shape reconstruction model does not rely on mechanical models. It has the advantages of being simple to solve, highly accurate and fast in computation, making it suitable for real-time control of continuum robots.

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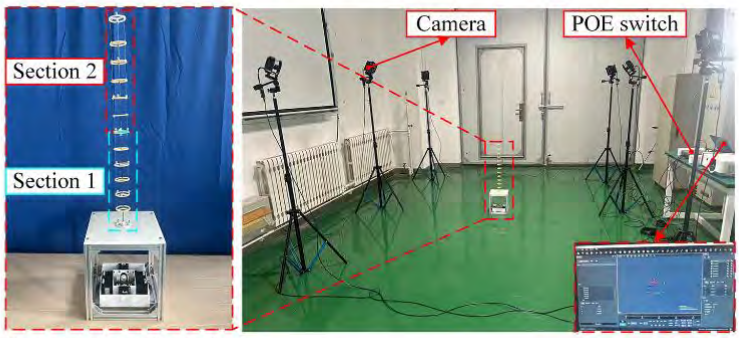
Figure 4 Continuum robot shape measurement experimental platform



Source: Authors' own work

How NOKOV Contributes to the Research

An experimental platform is set up to measure the spatial shape of the continuum robot, consisting of the continuum robot and Nokov optical 3D motion capture system. The motion capture system comprises six motion capture cameras, model Mars1.3H, with a resolution of 1,280x1,024. The camera is mounted on three-axis head, and each camera is connected to the POE switch via network cables. The POE switch is directly connected to a computer via network cables. The reflective markers are pasted on the prototype of the continuum robot, and the spatial positions of the reflective markers are obtained by the motion capture camera. The actual shape of the continuum robot is obtained by fitting the reflective markers. Figure 4shows the experimental platform.

Citation Tang S, Ji J, Zhi Y, et al. A novel inverse kinematics and shape reconstruction method for continuum robots[J]. Industrial Robot: the international journal of robotics research and application, 2025, 52(3): 415-424.

Link https://www.emerald.com/insight/content/doi/10.1108/ir-08-2024-0391/full/html

A probabilistic geometric imperfection model for uncertainty quantification of inflatable beams with local structure instability

Keywords

nflatable beams, Locally wrinkling, Initial geometric imperfection, Collapse load, Uncertainty quantification

Abstract

Experimental data of inflatable beams present strong randomness that is caused by a locally post-buckling behavior, sensitive to boundary condition and initial geometric imperfection. It is so difficult for finite element analysis (FEA) to predict the post-buckling nonlinear behavior and collapse load accurately, and un-certainty quantification (UQ) still remains an open problem for inflatable beams. The paper proposes a new probabilistic geometric imperfection model that is used for post-buckling FEA and completes the uncertainty quantification of inflatable beams using Gaussian process regression (GPR). Differing from an empirical selection of buckling eigenmodes, the proposed imperfection model introduces two random variables describing un-certainties of material and structural coefficients. With scarce experimental data, the model is validated, and then the predicted confidence interval (CI) of load-deflection curves obtained by FEA and GPR can cover disperse experimental data. The cost of experiments for uncertainty quantification is thus saved greatly. The study shows that amplitude and location of wrinkles are two key factors influencing the collapse load of inflatable beams. The predicted CI can be used for structural design based on its lower bound and for structural health monitoring (SHM). It suggests that usage of the proposed geometric imperfection model could be enhanced by popular machine learning or artificial intelligence technologies, such as Convolutional Neural Networks (CNN) and Generative Adversarial Networks (GAN), for real-time SHM in future.

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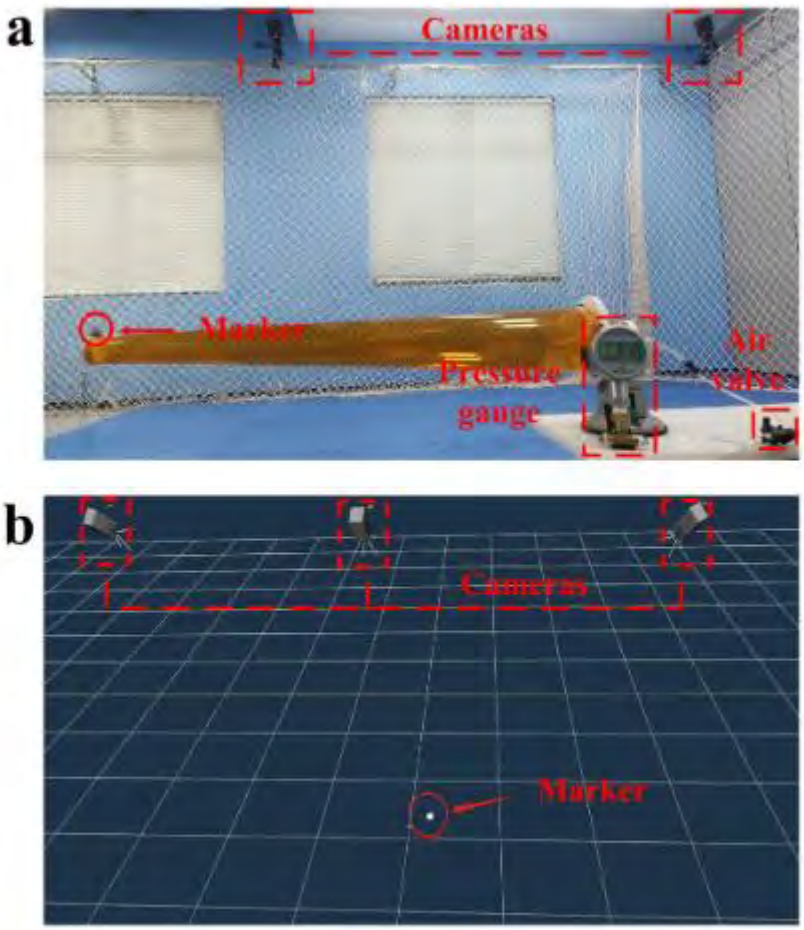

Fig. 12. Experimental setup of Beam (52.24, 0.44): (a) Hardware; (b) NOKOV software.

How NOKOV Contributes to the Research

Fig. 12.Experimental setup of Beam (52.24, 0.44): (a) Hardware; (b) NOKOV software

Citation Cen Z, Ge Y, Li S, et al. A probabilistic geometric imperfection model for uncertainty quantification of inflatable beams with local structure instability[J]. Thin-Walled Structures, 2025: 113575.

Link https://www.sciencedirect.com/science/article/abs/pii/S0263823125006688

Adaptive Load-Dependent Sim2Real Framework for Path Tracking Toward Tendon-Driven Continuum Robots

Keywords

Continuum robot (CR), hypothesis compensation, path tracking

Abstract

Continuum robots (CRs) are crucial for executing intricate tasks in constrained anatomical spaces. However, challenges such as actuator latency, backlash, and tendon pretensioning can limit their effectiveness. In this article, we introduce an adaptive load-dependent simulation to the real-world framework for path tracking in tendon-driven CRs, essential for enhancing the dexterity and precision required in minimally invasive surgical procedures. We propose a fixed-pose inverse kinematics control method integrating virtual degrees of freedom into end-effector planning to facilitate six-dof navigation. Then, it establishes a relationship between overall tendon loading and motor actuation, paving the way for employing the learning-based neural network for accurate calibration of the robot's physical model, enabling arbitrary trajectory tracking without the need for external shape-sensing sensors. Our method maintains a maximum 3-D root-mean-square error (RMSE) of 5.01 mm across diverse trajectory types, achieving a directional discrepancy RMSE of 0.114 radians. This demonstrates a significant improvement in tracking accuracy, reducing tracking errors by 86.1% compared to the noncompensated approach. The findings of this study highlight the potential of our approach to bridge the gap between simulation and real-world applications, ultimately enhancing operational efficiency and patient outcomes in robotic-assisted surgeries.

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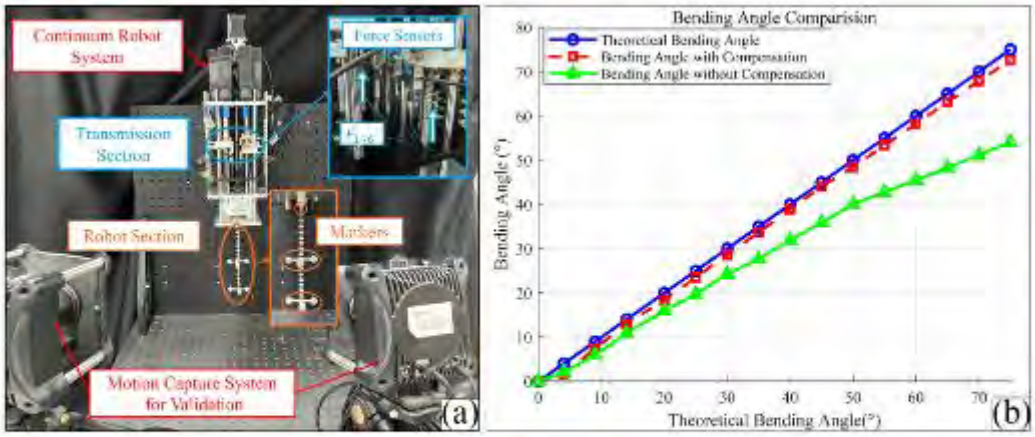

Fig. 8. (a) Continuum system configuration. (b) Single-segment bending compensation test.

How NOKOV Contributes to the Research

Marker position were tracked using a 3-D optical capture system consisting offour external cameras (Mars 4H, NOKOV, China) operating ata sampling rate of 180 Hz. The system achieves a 3-D accuracy of±0.10 mm, ensuring precise measurement of the robot's deflections.

Citation Yao, S., Luo, P., Yue, Y., Chen, Y., Yan, H., & Meng, M. Q. H. (2025). Adaptive Load-Dependent Sim2Real Framework for Path Tracking Toward Tendon-Driven Continuum Robots. IEEE/ASME Transactions on Mechatronics.

Link https://ieeexplore.ieee.org/document/11008581

Adaptive sliding mode tracking and disturbance rejection control for cable-driven continuum robots in endoscopic surgery

Keywords

Adaptive tracking control, Cable-driven continuum robots, Disturbance rejection, Extended state observer, Integral terminal sliding mode

Abstract

Cable-driven continuum robots (CDCR) demonstrate considerable potential for application in endoscopic surgery owing to their high flexibility. However, their nonlinear deformation, compounded by disturbance interactions, leads to reduced control precision during environmental contact. Consequently, conventional control methods are inadequate for addressing both system uncertainties and dynamic disturbances. An adaptive integral terminal sliding mode control method with a nonlinear extended state observer (NESO-AITSMC) is proposed to achieve disturbance rejection control for nonlinear CDCR systems under multi-source disturbance coupling. Firstly, an integral terminal sliding mode surface incorporating a nonlinear logarithmic term is designed to synergistically optimize transient response and steady-state accuracy. Secondly, an adaptive gain law based on sliding-mode state feedback is developed to mitigate performance degradation in regions with concentrated uncertainties caused by fixed gains. Subsequently, a finite-time convergent nonlinear extended state observer (NESO) is formulated to achieve real-time compensation for model uncertainties and external disturbances. Finally, the global asymptotic stability of the closed-loop system is rigorously established using Lyapunov stability theory. Simulation and experimental results indicate that, under model uncertainty and external disturbances, the proposed method reduces peak tracking errors in the X, Y, and Z axes by 30.3%, 78.2%, and 51.7%, respectively, compared with conventional controllers, while single-axis peak tracking errors are maintained within 4 mm. This study validates the effectiveness of the proposed control scheme in enhancing the disturbance rejection capability and trajectory tracking precision of CDCR.

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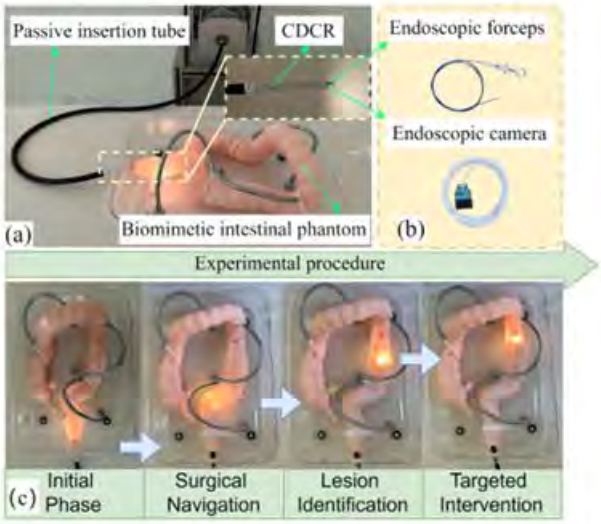

Fig. 22. Phantom experiments. (a) experimental setup. (b) the utilized endoscopic biopsy forceps and the camera. (c) procedure of the intestinal model for endoscopic interventions.

How NOKOV Contributes to the Research

5.1. Trajectory tracking experiment
The experimental verification system, as depicted in Fig. 16(a), comprises three primary components. The robotic platform includes a continuum robot, driving motors, and a support platform. The fabrication of PLA vertebral units for the bionic continuum mechanical body is realized using fused deposition modeling (FDM) technology. The mechanical body consists of two segments, each possessing independent rotational and bending degrees of freedom. Collectively, these segments form a bionic flexible structure with a 10 mm diameter and an effective length of 88 mm. An instrument channel is reserved at the robot's center, accommodating an endoscopic camera (640x480 resolution) and a micro biopsy forceps. The driving system comprises six ST3215 servo motors, with three motors assigned to each motion joint. The attitude adjustment of the robot end-effector is achieved via cable traction. The motors provide a maximum torque of 0.53 Nm and a rotational speed of 8.73 rad/s, satisfying the requirements for precise surgical positioning. To acquire pose information, a NOKOV Motion Capture System is employed. An ESP32 development board is integrated into the control core, enabling data communication with MATLAB at a baud rate of 115200 bps.

Citation Zhang M, Chen Y, Gao Y, et al. Adaptive sliding mode tracking and disturbance rejection control for cable-driven continuum robots in endoscopic surgery[J]. Control Engineering Practice, 2026, 168: 106684.

Link https://webofscience.clarivate.cn/wos/alldb/full-record/WOS:001637369800001

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Adjustable-Stiffness Hip Exoskeleton with Flexible Energy-Storage Module for 3D Gait Correction

Keywords

lower-limb exoskeleton; gait correction; adjustable stiffness; flexible energystorage; hip assistance

Abstract

This paper presents a lower-limb hip exoskeleton system integrated with an adjustable-stiffness flexible energy-storage module for three-dimensional gait correction. This system features a modular flexible mechanical design and a stiffness-gain scheduled PID control strategy for dynamic, personalized assistance. Based on biomechanical analysis of the hip joint, a 3D gait correction model was constructed targeting impairments in flexion, abduction, and adduction. The control strategy adjusts system stiffness in real-time according to gait phase and user-specific parameters. Experimental results demonstrated that the exoskeleton effectively reduced joint trajectory variability (22% decrease in standard deviation of hip flexion angle) and improved muscle activation patterns (21.4% increase in rectus femoris activity), thereby enhancing gait symmetry and stability. This study offers a feasible mechatronic solution for pathological gait correction with promising clinical applicability.

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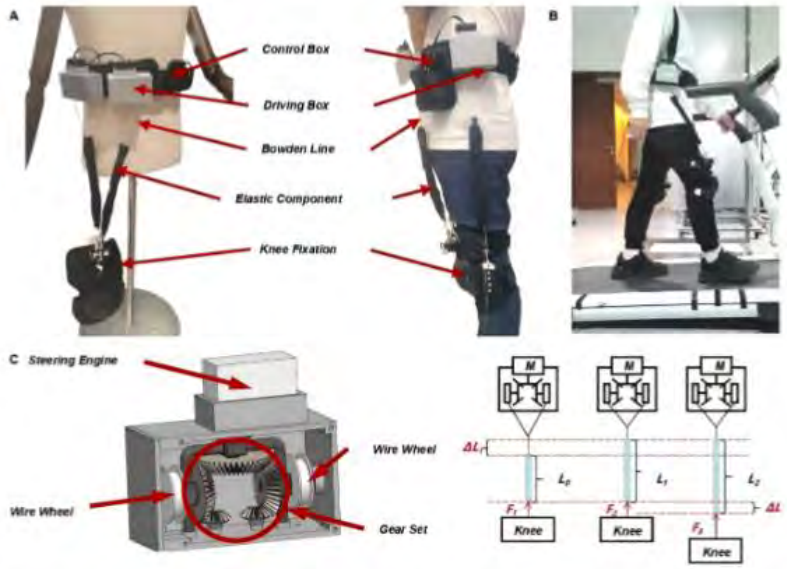

Figure 1. Overall Mechanical Design and Human–Device Coupling of Lower-Limb Hip Exoskeleton: **(A)** Prototype of the Lower-Limb Hip Exoskeleton Mechanis. **(B)** Human–Exoskeleton Interface During Walking. **(C)** Drive Box Structure and Force Transmission Mechanism.

How NOKOV Contributes to the Research

4.1.2. Experiment Device
IMUs and EMG sensors (MyoMOTION, Noraxon, Scottsdale, AZ, USA) were used to capture and display three-dimensional joint angles and accelerations of the human body in real-time using data acquisition software (MR3, Noraxon, Scottsdale, AZ, USA). Five IMUs were affixed to specific anatomical locations: the pelvis, left thigh, left shank, right thigh, and right shank. EMG sensors were placed on the rectus femoris, adductor longus, and gluteus medius muscles to measure muscle activation levels during the gait cycle. The placement of these sensors followed standard anatomical guidelines to ensure accurate data collection. The sampling frequency was set to 100 Hz. Each IMU provided angle measurements with a static accuracy of ±0.2° and a dynamic accuracy of ±0.4°.
Joint angle measurements were obtained using a motion-capture system (Nokov, Nokov Science & Technology, Beijing, China). Nineteen reflective markers were positioned on specific anatomical landmarks according to the Davis protocol [32,33]. The trajectories of these markers were tracked and analyzed using the motion capture software. The average and standard deviation of lower-limb joint angles were calculated. From the data, joint angles at critical points during the gait cycle, such as heel strike and toe-off, were extracted across multiple consecutive cycles. These parameters include the hip, knee, and ankle angles during both the stance and swing phases, as well as the total duration of each gait cycle.

Citation Xu T, Sun Z, Li S, et al. Adjustable-Stiffness Hip Exoskeleton with Flexible Energy-Storage Module for 3D Gait Correction[J]. Machines, 2025, 13(10): 959.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001601977700001

An adaptive lumped-mass dynamic model and its control application for continuum robots

Keywords

Continuum robot, Lumped-mass model, Dynamics, Parameter estimation

Abstract

Dynamic modeling for continuum robots remains challenging due to their large nonlinear deformation and the variation of dynamic parameters during movement. In this paper, a lumped-mass dynamic model (LMD) for a continuum robot is constructed including elastic and viscous parameters in the robotic joints. Then the appropriate dynamic parameters (e.g. spring and damping coefficients of the LMD) with respect to the motion status (e.g. position and velocity of the robot) are estimated using a Genetic Algorithm (GA). Based on the obtained data set, a Multi-Layer Perception (MLP) is trained to establish a direct mapping from the motion status to the dynamic parameters, so the LMD can tune its parameters in real-time when moving within the workspace, resulting an adaptive lumped-mass dynamic model (ALMD). Compared to the fixed-parameter LMD, the modeling error of the ALMD is reduced by up to 60.2 %. Finally, a feedforward controller is implemented to control a continuum robotic prototype using the presented ALMD, reducing the maximum tracking error by 67.5 %.

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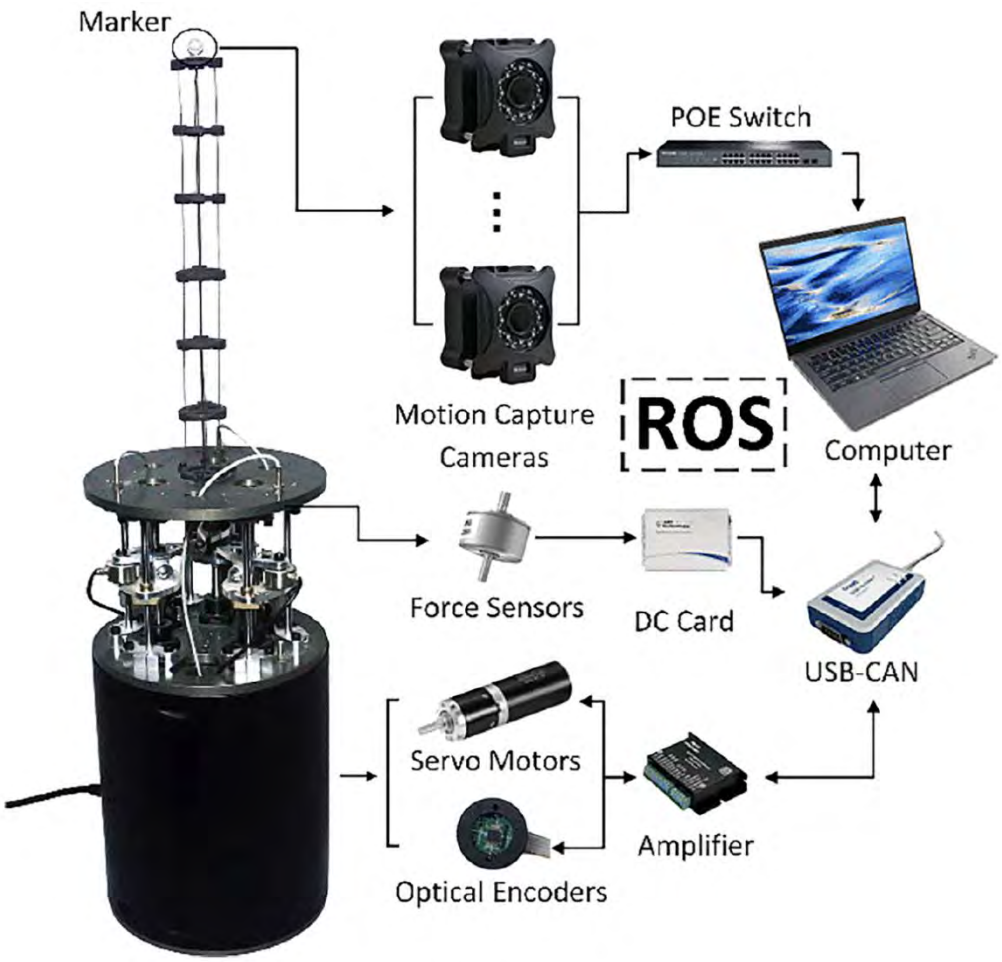

Fig. 11. Prototype of the continuum robot.

How NOKOV Contributes to the Research

The continuum arm contains a backbone, three driving rods distributed 120° apart and 7 constraint disks. The total length of the arm is 300 mm, and the sets of servo motors and ball screws to pull or push the driving rods. An optical motion capture system including four cameras and a marker (The NOKOV Inc., China) is used to measure the position of the arm tip within its operational space.

Citation Xu Zhang, Chenghao Yang, Zhibin Song, Mojtaba A. Khanesar, David T Branson, Jian S. Dai, Rongjie Kang,An adaptive lumped-mass dynamic model and its control application for continuum robots, Mechanism and Machine Theory,Volume 201,2024,105736,ISSN 0094-114X, https://doi.org/10.1016/j.mechmachtheory.2024.105736.

Link https://www.sciencedirect.com/science/article/abs/pii/S0094114X24001630

An explicit nonlinear model for large spatial deflections of symmetric slender beams

Keywords

Large spatial deflection, Symmetric beams, Compliant mechanism, Quaternion, Adomian polynomials

Abstract

Flexible slender beams are commonly used in compliant mechanisms and continuum robots. However, the modeling of these beams can be complicated due to the geometric nonlinearity becoming significant at large elastic deflections. This paper presents an explicit nonlinear model for large spatial deflections of a slender beam with uniform, symmetrical sections subjected to general end-loading. The elongation, bending, torsion, and shear deformations of the beams are modeled based on Timoshenko's assumptions and Cosserat rod theory. Subsequently, the nonlinear governing differential equations for the beam are derived from the quaternion representation of the rotation matrix. The explicit load–displacement relations of the beam are obtained using the improved Adomian decomposition method. This method is superior to the classical Adomian decomposition method in terms of convergence rate and domain. The convergence and superiority of the method are also rigorously demonstrated. Simulations are provided to verify the one-, two-, and three-dimensional deflections of beams. Real-world experiments have also been performed to validate our method's effectiveness with two different beam configurations. The results indicate that the proposed method accurately estimates large spatial deflections of flexible beams.

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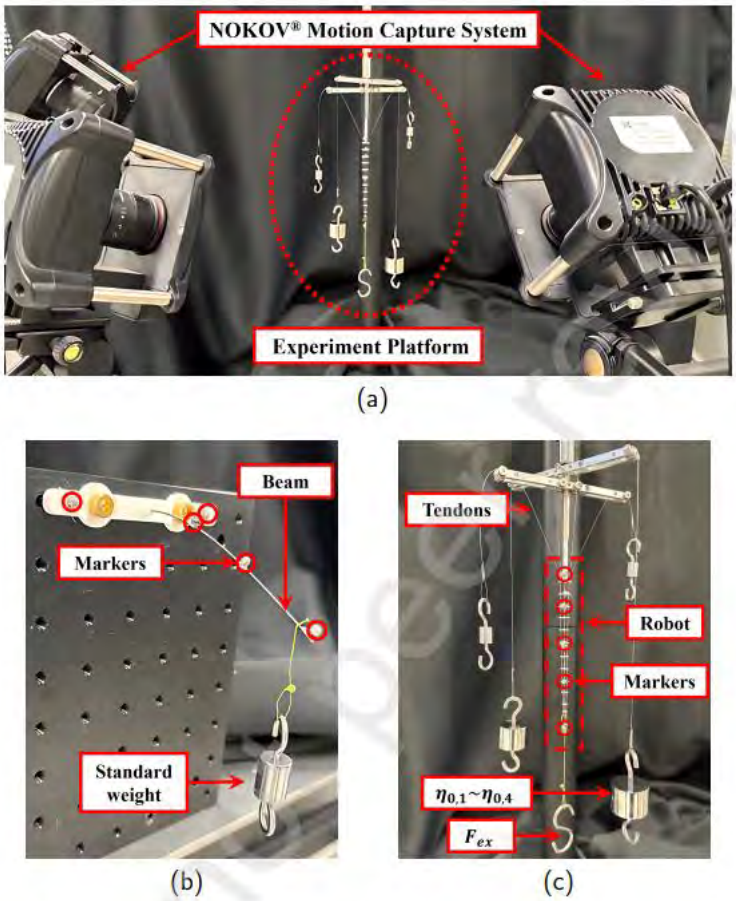

Figure 6: Devices for experimental validation. (a) Measuring devices. (b) Setup for Experiment #1. (c) Setup for Experiment #2.

How NOKOV Contributes to the Research

This subsection will show experimental verifcation. The validation system is shownin Fig. 6. The profle of the beam is reconstructed by some 3-mm-diameter markers. It'snoticed that the offsets between each marker and its corresponding beam are measured beforethe experiment. The three-dimensional capture system consisting of five optical cameras(Mars 4H. NOKOV®,China)with 180 Hz measures the robot defections by capturingmarkers (only three cameras are shown in Fig, 6a). The 3D accuracy of the system is ±0.40mm.

Citation Chen Y, Yao S, Liu L, et al. An explicit nonlinear model for large spatial deflections of symmetric slender beams[J]. International Journal of Non-Linear Mechanics, 2024, 167: 104910.

Link https://www.sciencedirect.com/science/article/abs/pii/S0020746224002750

Analysis of Finger Motions for Assisting Spoon Scooping with Soft Actuators

Keywords

Wrist, Actuators, Measurement units, Tracking, Force, Inertial navigation, Grasping, Soft robotics, Muscles, Complexity theory

Abstract

Assistance with eating for patients with hand muscle weakness and limited wrist mobility is important. There have been devices developed for feeding assistance, though most have not used the residual hand function of patients, which may increase the risk of disuse syndrome and loss of joy in life. In addition, soft gloves have been recently used as a way for providing assistance for patients with hand mobility. In particular, one previous study achieved spoon grasping using a soft glove on the hand, which opens the possibility of assist-as-needed. However, scooping and transporting that are required for eating with a spoon have not been investigated in the study. Our ultimate goal is to realize soft actuator assisted self-feeding for the persons with partial hand function impairment. In this study, we analyze the finger-driven spoon-scooping motion for determining significantly associated finger joints and how to control them for assisting the spoon-scooping. The reason for not including wrist-involved scooping is the force and bidirectional control it needs, which might increase the complexity of devices and risk of assisting. The finger-driving spoon scooping motion was measured by motion tracking and inertial measurement units, after that, an assumption about multiple types of finger-driving was made and verified with experiments on soft-actuators assisted finger driven scooping with a dummy hand. As a result, the scooping angle achieved by our device was found to be a maximum of 63.6 degrees, exceeding 52 degrees, the scooping angle required. The results demonstrate the possibility of assistance with scooping with soft actuators. This study is an important step towards our ultimate goal.

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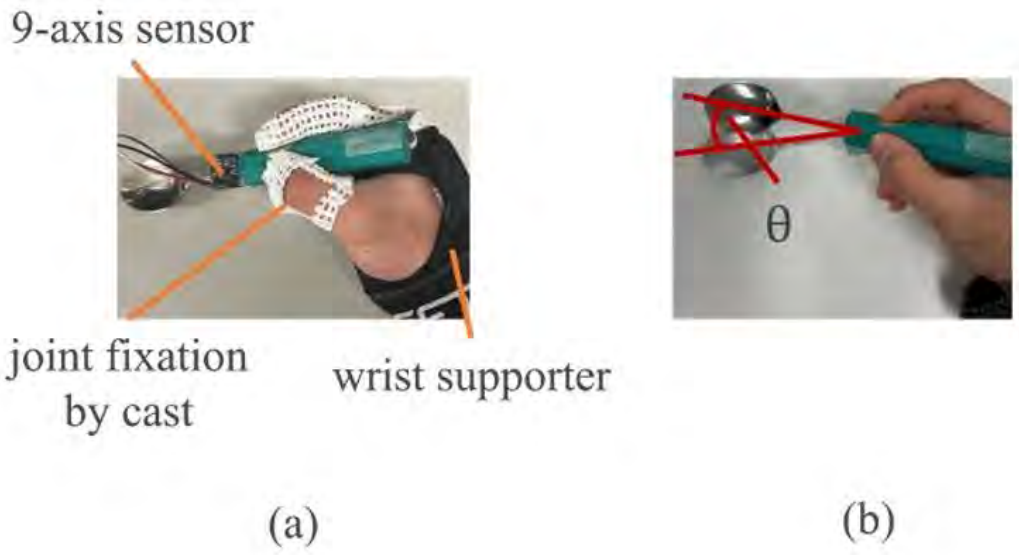

Figure 4. (a) finger joint fixation and spoon angle measurements in Experiment 2, (b) definition of lateral deviation angle

How NOKOV Contributes to the Research

A. Experiment 1: Simultaneous Measurement of Scooping Angle and Joint Angle using Optical Motion Tracking
Nokov optical 3d motion capture system (Mars 1.3 HW, Beijing NOKOV Science & Technology Co., Ltd., CN) was used to capture repeated scooping movements using the fingers as shown in Fig. 1. The appearance of the experiment is shown in Fig. 3(c). For this experiment, only the angles of the joints of the thumb, index finger, and middle finger, which are necessary for spoon feeding, were calculated. To ensure the reproducibility of the experiment, markers were attached to gloves instead of directly to the hand, as shown in Fig. 3(b). Similarly, the markers were attached to the spoon, also shown in Fig. 3(a). The names of each marker were defined in Fig. 3(a) and Fig. 3(b).

Citation Tanizaki Y, Tortós-Vinocour P E, Matsunaga F, et al. Analysis of Finger Motions for Assisting Spoon Scooping with Soft Actuators[C]//2024 17th International Convention on Rehabilitation Engineering and Assistive Technology (i-CREATe). IEEE, 2024: 1-6.

Link https://ieeexplore.ieee.org/document/10776454

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Anchoring Morphological Representations Unlocks Latent Proprioception in Soft Robots

Abstract

This research addresses the need for robust proprioceptive methods that capture the continuous deformations of soft robots without relying on multiple sensors that hinder compliance. The authors propose a vision-based deformation learning strategy called latent proprioception, which anchors the robot's overall deformation state to a single internal reference frame tracked by a miniature onboard camera. Through a multi-modal neural network trained on simulated and real data, the authors unify motion, force, and shape measurements into a shared representation in latent codes, inferring unseen states from readily measured signals. The experimental results show that this approach accurately reconstructs full-body deformations and forces from minimal sensing data, enabling soft robots to adapt to complex object manipulation or safe human interaction tasks. The proposed framework exemplifies how a vision-based deformable learning approach can inform and enhance robotics by reducing sensor complexity and preserving mechanical flexibility. The authors anticipate that such hybrid system codesign will advance robotic capabilities, deepen the understanding of natural movement, and potentially translate back into healthcare and wearable technologies for living beings. This work paves the way for soft robots endowed with greater autonomy and resilience.

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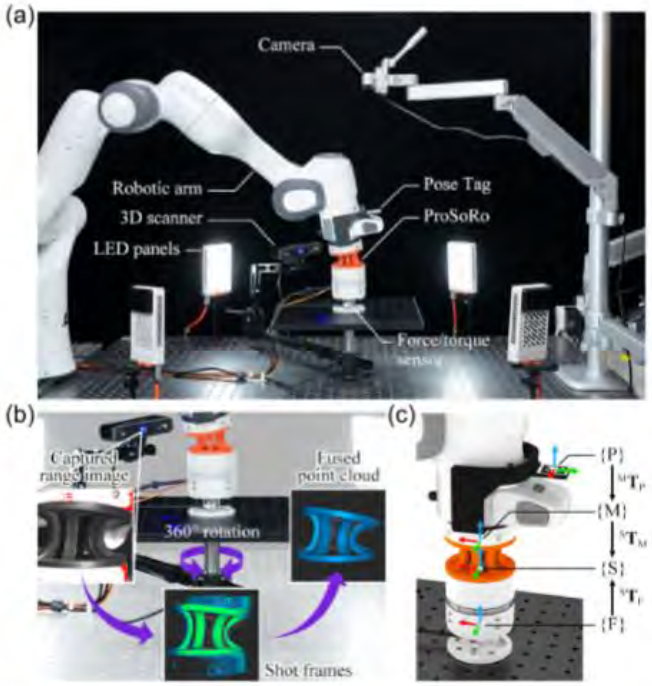

Figure 8. Setup for sim-to-real evaluation of crossmodal inference by MVAE. a) Experiment setup, including robotic arm, 3D scanner, camera, pose tag, force/torque sensor, LED panels, and ProSoRo. b) Range image, single-shot frame (green), overlapping previous point cloud (blue), and fused point cloud of ProSoRo by the 3D scanner. c) Relation among the force/torque sensor's coordinate $\{F\}$, the pose tag's coordinate $\{P\}$, the anchor frame's coordinate $\{M\}$, and the ProSoRo's coordinate $\{S\}$.

How NOKOV Contributes to the Research

To evaluate the performance of the tendon-driven platform, we applied step signals to the platform on six dimensions, respectively, and recorded the motion of the ProSoRo by MoCap (Mars2H, NOKOV), as shown in Figure 12. The step translations along the x and y axes vary with a step size of 2 mm, increasing from 0 to 10 mm, then decreasing to -10 mm, and finally returning to 0 mm, while that along the z axis varies with a step size of 1 mm, decreasing from 0 to -5 mm, and then returning to 0 mm. Similarly, the step rotation in each direction varies with a step size of 5°, increasing from 0° to 25°, then decreasing to -25°, and finally returning to 0. A pole with four markers was fixed on the ProSoRo, and MoCap captured the positions of the markers, which were then converted into the motion of the ProSoRo..

Citation Han X, Guo N, Xu R, et al. Anchoring Morphological Representations Unlocks Latent Proprioception in Soft Robots[J]. Advanced Intelligent Systems, 2025: 2500444.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001520618800001

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Axis-space framework for cable-driven soft continuum robot control via reinforcement learning

Keywords

Biomedical engineering， Information technology

Abstract

Cable-driven soft continuum robots are important tools in minimally invasive surgery (MIS) to reduce the lesions, pain and risk of infection. The feasibility of employing deep reinforcement learning (DRL) for controlling cable-driven continuum robots has been investigated; however, a considerable gap between simulations and the real world exists. Here we introduce a deep reinforcement learning-based method, the Axis-Space (AS) framework, which accelerates the computational speed and improves the accuracy of robotic control by reducing sample complexity (SC) and the number of training steps. In this framework, the SC was reduced through the design of state space and action space. We demonstrate that our framework could control a cable driven soft continuum robot with four tendons per section. Compared with the Double Deep Q-learning Network (DDQN) controller, the proposed controller increased the convergence speed by more than 11-fold, and reduced the positioning error by over 10-fold. This framework provides a robust method for soft robotics control.

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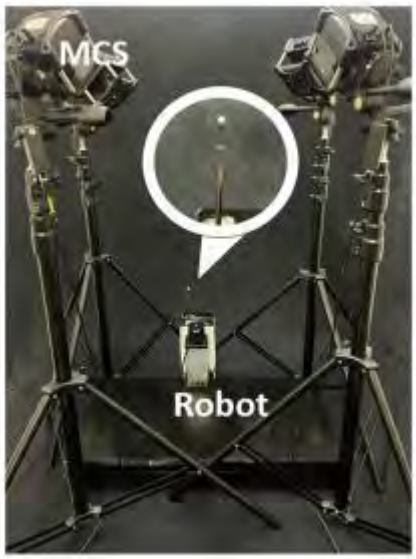

How NOKOV Contributes to the Research

Here, both the real-timeend tip positions and the target positions can be considered as acollection of pixel dots with a diameter of 0.5 mm due to theaccuracy of the MCS (NOKOV Inc., CHINA) used. Therefore,the state space contains afinite number of vectors. In work space,assuming there are 2n(n∈N\) states alongxandyaxes,2m(m∈N\) states alongzaxis, there are $2\pi mn^2$ states totally.

Citation Wei D, Zhou J, Zhu Y, et al. Axis-space framework for cable-driven soft continuum robot control via reinforcement learning[J]. Communications Engineering, 2023, 2(1): 61.

Link https://link.springer.com/article/10.1038/s44172-023-00110-2

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Behavior-Predefined Adaptive Control for Heterogeneous Continuum Robots

Keywords

Adaptive kinematic control, heterogeneous continuum robots, prescribed performance

Abstract

Continuum robots have great application value and broad prospects in various fields due to their dexterity and compliance. To fully exploit their advantages, it is crucial to develop an effective, accurate and robust control system for them. However, research on continuum robot control is still in its infancy and there are many problems remaining unsolved in this field. In particular, this paper focuses on the task-space behavior and the generic control of heterogeneous continuum robots. First, a controller is proposed to achieve the kinematic motion control and visual servoing of continuum robots with predefined task-space behavior. The predefined behavior is twofold: prescribed task-space error and predefined convergence time. Then, the proposed controller is integrated with a velocity-level kinematic mapping estimator to obtain a model-free control system, which is applicable to heterogeneous continuum robots. Furthermore, a re-adjustable performance function is proposed to ensure the effectiveness and robustness of the proposed control system in the presence of external disturbance. Finally, extensive simulations and experiments are performed based on heterogeneous continuum robots, including the cable-driven continuum robot, the parallel continuum robot, the concentric-tube robot, the flexible endoscope, and the pneumatic continuum robot. Our results demonstrate that the task-space error of heterogeneous continuum robots complies with the prescribed boundaries and converges to steady state in predefined time, which reveals the efficacy of the proposed control method.

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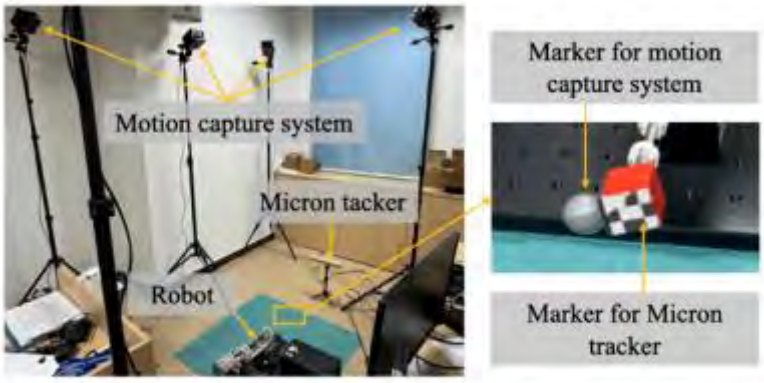

Figure 37. Experiment setup for validating the accuracy of the Micron Tracker H3-60.

How NOKOV Contributes to the Research

To demonstrate that using a checkerboard and a vision-based method can accurately track the robot end-effector's position, we take the position data captured from physical experiments by the NOKOV motion capture system as the ground truth. As depicted in Figure 37, the markers for the motion capture system and the Micron Tracker are attached to the end effector.

Citation Tan, Ning, et al. "Behavior-predefined adaptive control for heterogeneous continuum robots." The International Journal of Robotics Research 44.1 (2025): 65-95.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001251398800001

Chained Spatial Beam Constraint Model: A General Kinetostatic Model for Tendon-Driven Continuum Robots

Keywords

3-D motion, continuum robots, kinetostatic modeling, multisection robots

Abstract

The profile estimation for continuum robots is a crucial problem concerning automatically controlling robots. The conventional method is based on the Cosserat rod theory, which is limited by the dependence of the convergence on the initial guess and computational complexity. To tackle these issues, this article proposes a general kinetostatic model to estimate the profile of the tendon-driven continuum robot (TDCR). We first abstract the backbone of the TDCR as an Euler–Bernoulli beam and then derive the spatial beam constraint model of a circular cross-section beam without considering torsion and shear. Next, taking a single-section TDCR as an example, we provide comprehensive modeling, considering the driving tendon tensions, friction, gravity, and external forces. Subsequently, an algorithm based on the chained spatial beam constraint model is proposed to estimate the robot's profile. The method can be generalized to the TDCR with different configurations. Simulations demonstrate the accuracy, computational efficiency, and computational success rate of our method, as well as its advantages over the state-of-the-art. Real-world experiments have also been performed to validate the effectiveness of our method with three different configurations of the TDCR.

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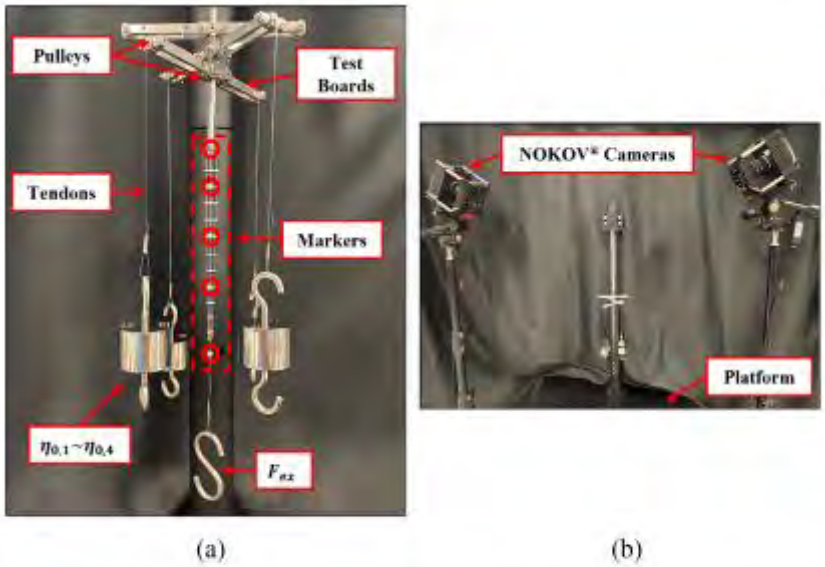

Fig. 7. Devices for experimental validation. (a) Actuator devices. (b) Measuring devices.

How NOKOV Contributes to the Research

The 3-D capture system consists of five optical cameras(Mars 4H, NOKOV, China) with 180 Hz measures the robot deflections by capturing markers \[only two cameras are shown in Fig.7(b)]. The 3-D accuracy of the system is ± 0.40 mm. The tip error, the distance between the measured and estimated tip positions, illustrates the model's accuracy.

Citation Chen Y, Yao S, Meng M Q H, et al. Chained spatial beam constraint model: A general kinetostatic model for tendon-driven continuum robots[J]. IEEE/ASME Transactions on Mechatronics, 2024, 29(5): 3534-3545.

Link https://ieeexplore.ieee.org/document/10403537

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Command Filtered Cartesian Impedance Control for Tendon Driven Continuum Manipulators with Actuator Fault Compensation

Keywords

Actuators, Accuracy, Trajectory tracking, Low-pass filters, Prototypes, Filtering algorithms, Manipulators, Trajectory, Impedance, Tendons

Abstract

Continuum robots are well-suited for constrained environments due to their superior flexibility and structural compliance. However, relying solely on passive compliance may lead to damage to both the robot and the surrounding environment. This work proposes a finite-time Cartesian impedance control scheme for tendon-driven continuum manipulators (TDCMs), where a second-order low-pass filter is used to adjust the reference trajectory according to the external robot tip force. The controller is designed using the command filtered backstepping method, and the finite-time stability is established by the designed Lyapunov function. In TDCM systems, the tendons operate antagonistically, and actuators often fail to quickly reach the desired tendon tension, leading to partial failures. To address this, we propose an actuator fault compensation algorithm to enhance system performance and reliability. We conducted trajectory tracking experiments on a multi-segment TDCM prototype, the results demonstrate that the designed Cartesian impedance controller achieves effective compliance control effect and high position control accuracy.

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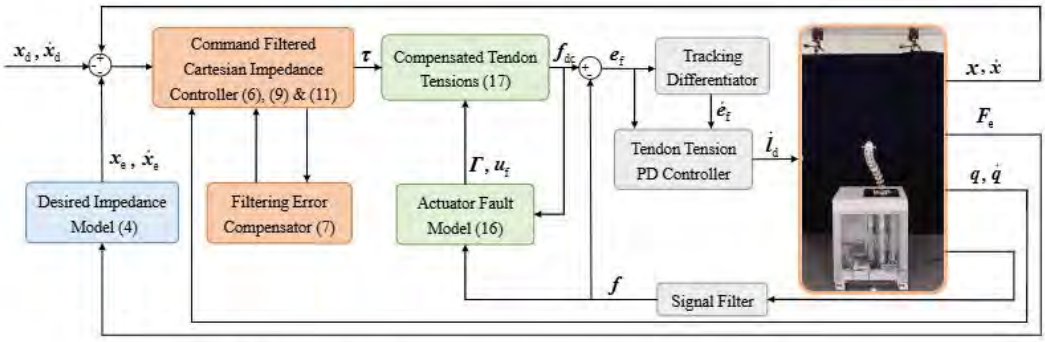

Fig. 2. Command filtered Cartesian impedance control scheme for the TDCM system.

How NOKOV Contributes to the Research

As shown in Fig. 2, a PDcontroller is used to control the tendon tension, where the derivative of the tension error is calculated by the tracking differentiator [26]. The motion capture system (Nokov,Mars2H, China) acquires the tip position and velocity of the TDCM at a rate of 60 Hz with the distally attached optical markers.

Citation Zheng X, Yu Z, Ding M, et al. Command Filtered Cartesian Impedance Control for Tendon Driven Continuum Manipulators with Actuator Fault Compensation[C]//2025 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2025: 13987-13993.

Link https://ieeexplore.ieee.org/abstract/document/11128624

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Controlling Soft Robotic Arms Using Hybrid Modelling and Reinforcement Learning

Keywords

Robot control, soft robotics, robot learning, reinforcement learning, hybrid modeling

Abstract

Soft robotic arms exhibit high deformability and degrees of freedom, which brings challenges in modeling accuracy and susceptibility to gravitational effects, resulting in imprecise control. This study proposes a reinforcement learning control strategy based on a hybrid model for precise control of soft robotic arms. The hybrid model is formulated by gathering a small dataset of analytical modeling errors of coordinates under various loading (0 g ~ 300 g) conditions, followed by employing a Multilayer Perceptron (MLP) to fit these errors, thereby reducing the forward kinematics MAEs (mean absolute errors) from a range of 75.2 mm ~ 95.3 mm to 5.9 mm ~ 9.1 mm. The reinforcement learning virtual environment is built upon the hybrid model and the Proximal Policy Optimization (PPO) algorithm is used to train control policies. The efficiency of the control policy is validated for different trajectories and loading conditions both in simulation and on the soft robotic arm prototype, revealing distance errors of 3.9 mm - 6.7 mm and 12.1 mm - 15.4 mm, respectively, representing 1.1% - 1.9% and 3.5% - 4.4% of the total arm length.

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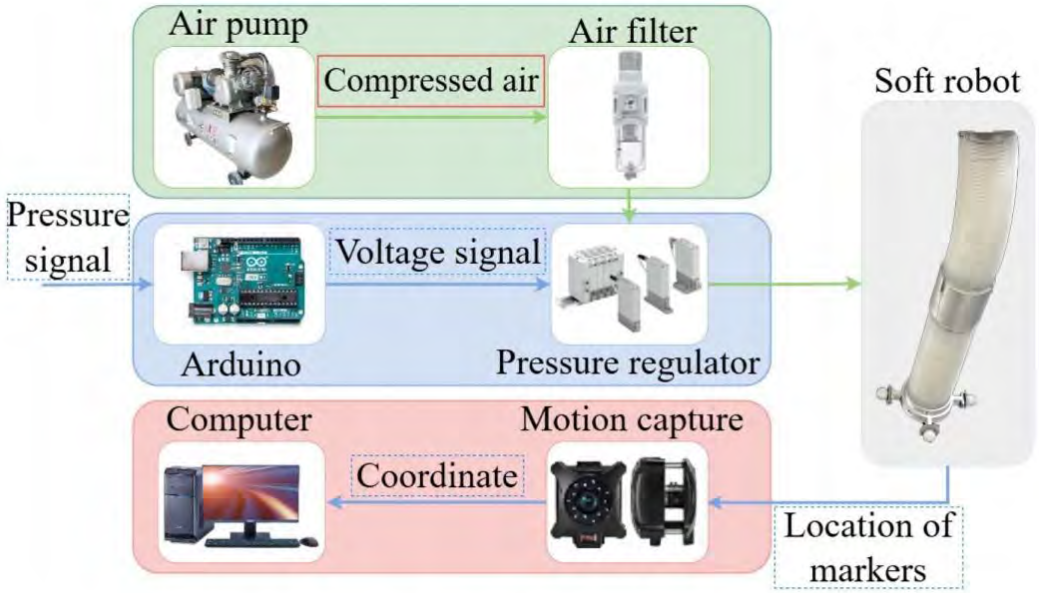

Fig. 6. Experimental setup for soft robotic arm tip coordinates collection.

How NOKOV Contributes to the Research

Finally, the motion capture system with eight Mars2H (NOKOV) cameras collects endpoint coordinates, which are transmitted to and stored on the computer. Initially, the soft robotic arm was suspended, and four reflective markers were affixed at the front endpoint of the arm. The coordinates of the centers of these four markers were then used as the endpoint coordinates.

Citation G. Lou, C. Wang, Z. Xu, J. Liang and Y. Zhou, "Controlling Soft Robotic Arms Using Hybrid Modelling and Reinforcement Learning," in IEEE Robotics and Automation Letters, vol. 9, no. 8, pp. 7070-7077, Aug. 2024, doi: 10.1109/LRA.2024.3418312.

Link https://ieeexplore.ieee.org/document/10569050

Curvature-Based Continuous Steering of Stiffness-Dominant Concentric Tube Robots

Keywords

Concentric tube robots, curvature based, continuous steering

Abstract

Existing works on controlling a concentric tube robot (CTR) mostly focus on the trajectory of its tip position or pose. In order to safely send CTRs in a confined lumen space, we propose to continuously steer the CTRs so that its entire shape will always attempt to approximate target curves over time. We focus on stiffness-dominant CTRs. Considering the differential geometry of such CTR shapes, we propose to work on the curvature domain to reduce the computational cost in searching the configuration of the CTRs. With our formulation, we model the curvature control of the CTR to find the optimal translation of each tube and then search for the rotation of the tubes to fit the target shapes. We demonstrate our method using sets of different target paths. The computational time per frame, ranging between 0.1 to 0.3 seconds across all experiments, highlights the efficiency of our approach in aligning the complete shape of the CTR with specified paths. Notably, for time-varying trajectories that could be reproduced by the CTR with its maximum deployment length reaching 150 mm, the root mean square error and median error were 0.98mm and 0.46mm, respectively. Note to Practitioners—This paper presents a novel approach for controlling stiffness-dominant CTRs, such that their entire shape consistently attempts to approximate target curves over time. This is crucial for applications such as navigation in confined anatomical spaces. Considering the differential geometry of these CTR shapes, we propose operating in the curvature domain. We model the curvature control of the CTR to determine the optimal translation for each segment, followed by searching for the rotation of the segments to fit the target shape. Our method avoids costly and computationally intensive full morphology evaluations while also achieving superior control accuracy, making it feasible for practical use in robotic surgery. In fact, this solution could be implemented in robot-assisted minimally invasive surgical platforms. Future work could explore adaptive modeling to address more complex clinical conditions, such as torsional deformations or variable tissue stiffness, or incorporate shape sensing for closed-loop control.

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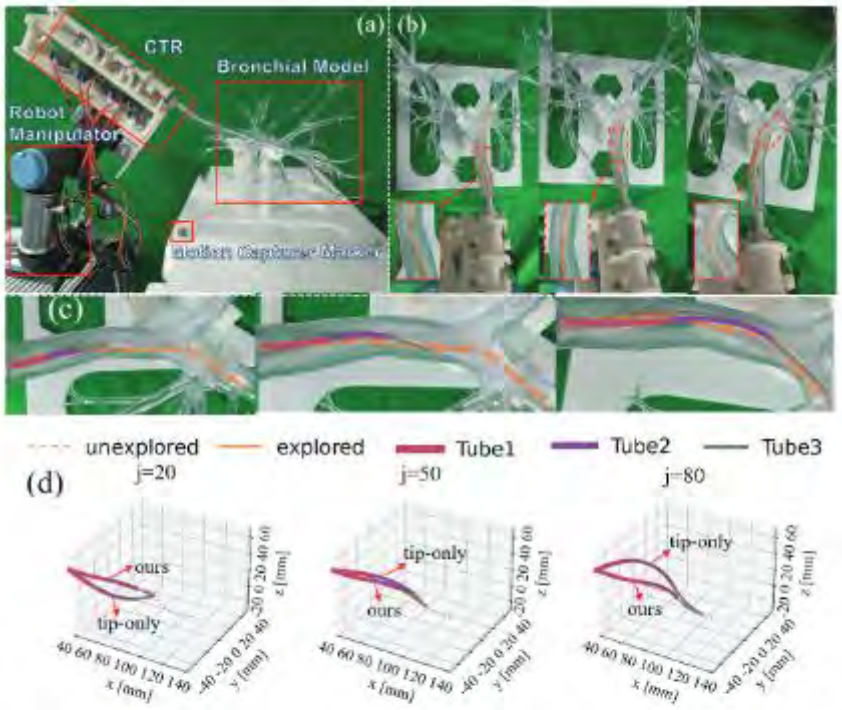

Fig. 9. (a) Real-world experiment on a physical phantom. (b) The CTR walks inside the bronchial model with its entire shape aligned with the centerline. (c) A zoomed-in view for the comparison between experimental and simulation results. (d) Continuous path following results on a freeform curve extracted from a bronchus path. Only controlling the tip trajectory may result in bad alignment of the CTR to the path.

How NOKOV Contributes to the Research

After assembling the physical model, we calibrated the relative pose between the robotic manipulator and the bronchial model using an optical motion capture system (Nokov Mars2H).

Citation Xie L, Zhu L, Jin X, et al. Curvature-Based Continuous Steering of Stiffness-dominant Concentric Tube Robots[J]. IEEE Transactions on Automation Science and Engineering, 2025.

Link https://ieeexplore.ieee.org/document/11006030

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Deployable-Structure-Based Artificial Muscles Generating Coded Forces

Abstract

Here mechanical metamaterials with shape memory alloys (SMA) are assembled to create a new kind of artificial muscle driven by response to temperature changes that generates pulling, pushing, and structurally coded and sequentially coded forces. The deformation and force response of a muscle unit can be geometrically tuned, and different forces are generated with two units arranged in parallel and in series. SMA sheets with different orientations controlling different units of a muscle chain can generate programmable force responses as a mixture of pulling and pushing forces. Combining structural coding with sequential coding, a wide range of force responses can be generated with a single muscle chain. It is shown that the proposed muscles can be applied in an arm-like mechanism to lift weights and to enable a car to cross a barrier. The principle explored in the work can be used to transform versatile origami- and kirigami-based structures into multifunctional actuators for many applications that can also be based on a variety of materials other than SMA.

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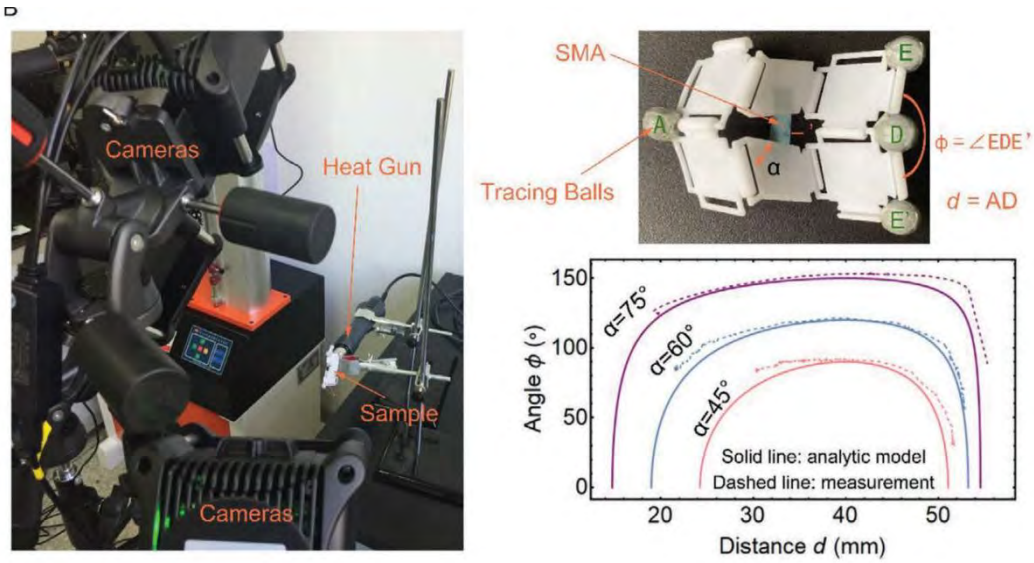

How NOKOV Contributes to the Research

With the insertion of a SMA sheet into a section of the kiri- muscle, the section exhibits the expected deformation (Figure 1A) in response to the temperature changes. To measure the structural deformation, four tracing balls were attached at points A, D, E and E′ of the kiri-muscle and were tracked by a six-camera motion capture system (Figure 2B).

Citation Yang N, Deng Y, Niu X. Deployable-Structure-Based Artificial Muscles Generating Coded Forces[J]. Advanced Materials Technologies, 2021, 6(9): 2100493.

Link https://onlinelibrary.wiley.com/doi/full/10.1002/admt.202100493

Design and Control of a Portable Soft Exosuit by Musculoskeletal Model-Based Optimization

Keywords

Exosuit, Walking assistance, Wearable robotics

Abstract

Universally applicable ankle assistance profiles can be generated through musculoskeletal model-based optimization, which can be applied to lightweight assistance conditions like unpowered exoskeletons and home rehabilitation. However, the effect of model-calculated optimal profiles on the energetics and kinematics of human walking still needs to be verified. Here, a portable soft exosuit was developed to apply model-based optimized moments and proportional biological moments to the ankle joint for comparison experiments. A low-level control strategy based on Gaussian process optimization was applied to each participant to track the target experimental moment accurately. Six participants walked on a treadmill at 1.25 ms−1 under one unpowered and two powered conditions, where metabolic costs and joint kinematics were measured. Compared with the Exo-off condition, the optimal assistance exosuit significantly reduced metabolic cost by an average of 6.23%, while the proportional condition was 2.09%. This study presents a simulation and optimization design paradigm using local musculoskeletal modeling to develop new assistance patterns more efficiently.

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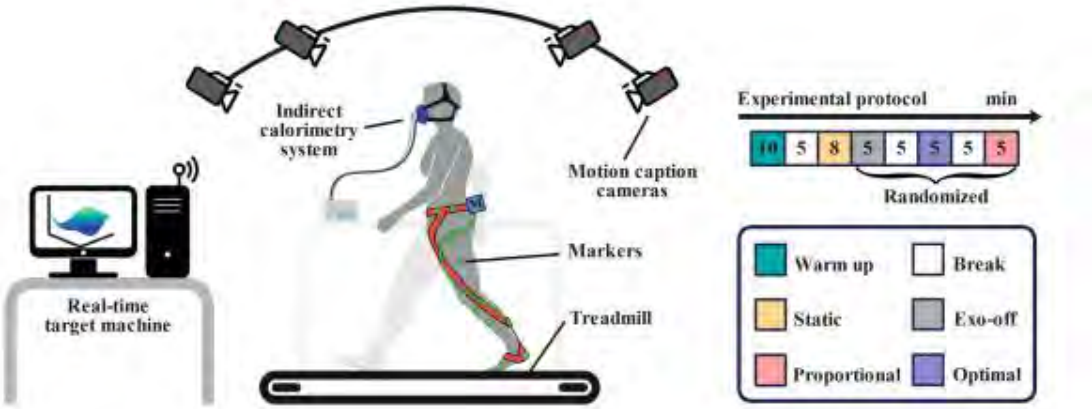

Fig. 4. Experimental platform and protocol.

How NOKOV Contributes to the Research

Metabolic rate was assessed using an indirect measurement method (K4b2,Cosmed, Italy) in four conditions: static, proportional assistance, optimal assis-tance, and Exo-off. In addition, carbon dioxide and oxygen data were collectedfrom the last two minutes of each condition, and the metabolic rate was cal-culated using the Brockway equation. The net metabolic rate was obtained bysubtracting the static metabolic rate from the average metabolic rate duringwalking. Lower limb kinematics was measured by a reflective marker motioncapture system (NOKOV Motion Capture System, China).

Citation Wang N, Wang Z, Li Z, et al. Design and Control of a Portable Soft Exosuit by Musculoskeletal Model-Based Optimization[C]//International Conference on Intelligent Robotics and Applications. Singapore: Springer Nature Singapore, 2023: 386-397.

Link https://link.springer.com/chapter/10.1007/978-981-99-6486-4_34

Design and Control of a Soft Hip Exoskeleton for Assisting Human Locomotion

Keywords

Hip exoskeleton, Wearable robotics, Walking assistance

Abstract

This paper presents a soft hip exoskeleton (SH-Exo) for healthy people's daily walking, which effectively provides an assisted force for hip extension through an actuation system with flexible Bowden cable. In addition, it is lightweight to satisfy the user's comfort and human-exoskeleton coordination. A control strategy based on Adaptive Hopf Oscillators (AHO) is proposed to achieve gait division and gait phase recognition. In order to achieve the goal of tracking the desired force curve accurately, a control strategy of the PID controller based on feedforward compensation is proposed. The results of the experiment show that the SH-Exo significantly reduces the metabolic cost of walking by an average of 5.3% in the Exo-on condition compared to the Exo-off condition.

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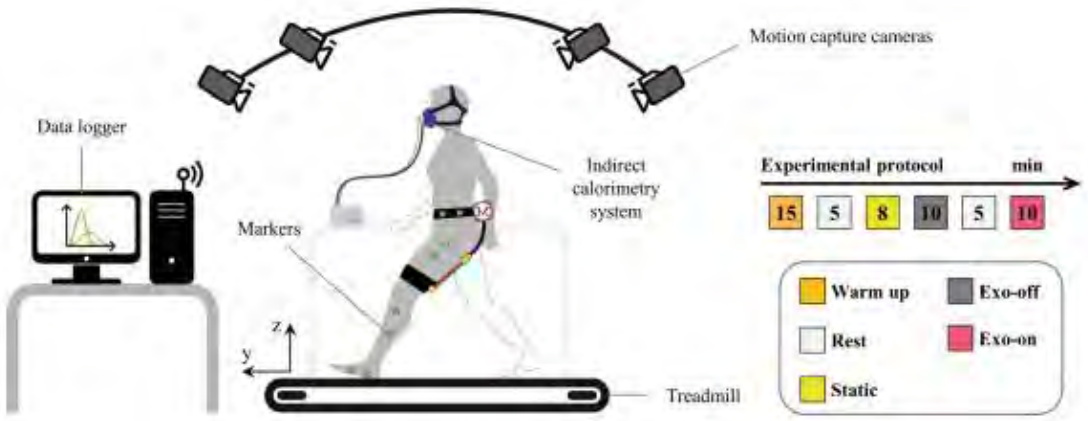

Fig. 3. The experimental platform and procedure

How NOKOV Contributes to the Research

The net metabolic rate was obtained by subtracting the metabolic rate of static from the total metabolic rate of walking. Lower limb motions were measured by a reflective marker motion capture system (NOKOV Motion Capture System, China), and joint angles were calculated from measured lower limb motions using inverse kinematics by software (MATLAB, MathWorks).

Citation Sun Z, Wang N, Zhang J, et al. Design and Control of a Soft Hip Exoskeleton for Assisting Human Locomotion[C]//International Conference on Intelligent Robotics and Applications. Singapore: Springer Nature Singapore, 2023: 374-385.

Link https://link.springer.com/chapter/10.1007/978-981-99-6486-4_33

Design and Development of Wearable Flexible Mechanical Arm Based on Iterative Learning Control*

Keywords

Human computer interaction, Training, Manufacturing processes, Spirals, Collaboration, Control systems, Stability analysis

Abstract

In this paper, the concept of "wearable" and "flexible" is combined to design and develop a wearable flexible robot arm, which can realize multi-person collaboration and human-computer interaction by adapting the corresponding end-effector. The main work includes: design and research on the structure and manufacturing process of wearable flexible robotic arm, mainly designing a casting molding process based on spiral compression scheme, and completing the design and manufacturing process of flexible robotic arm; A closed-loop control system for the flexible manipulator was built, and a control strategy based on the combination of iterative learning control and convolutional neural network was proposed. Through model training and simulation, it was proved that the proposed method can effectively improve the control accuracy of the end of the manipulator. An experimental test platform for the robotic arm was built, and related experiments were conducted. The experimental results showed that the wearable flexible robotic arm developed in this paper had a certain degree of completion, its motion effect and control accuracy reached the design expectations, and it had certain application prospects.

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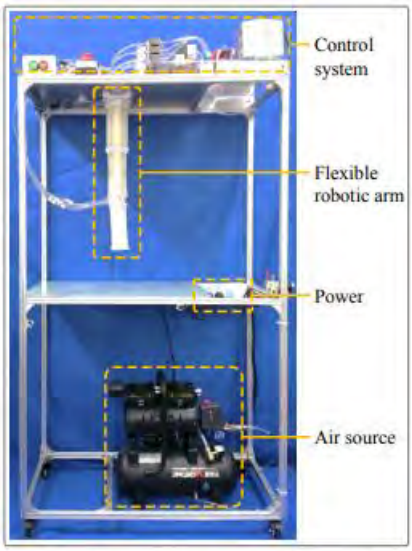

(a) Flexible robotic arm experiment platform

(b) Experimental measurement environment of flexible robotic

Fig. 14. Experimental platform and experimental environment for flexible robotic arm

How NOKOV Contributes to the Research

In this study, (NOKOV) Mars 2H series motion capture system is selected. It cancapture the spatial position and movement track of eachreflective mark in the visual range of the optical lens in realtime, and then carry out noise reduction and data processingthrough the supporting Seeker software, and then obtainthe point data.

Citation Cui Z, Xie L, Chen Z, et al. Design and Development of Wearable Flexible Mechanical Arm Based on Iterative Learning Control[C]//2023 IEEE International Conference on Robotics and Biomimetics (ROBIO). IEEE, 2023: 1-8.

Link https://ieeexplore.ieee.org/document/10355012

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Design and experimentation of the nested pneumatic soft actuator for hand exoskeleton

Keywords

Nested structure, Pneumatic soft actuator, Hand exoskeleton, Muscle fatigue reduction

Abstract

Frequent repetitive manual tasks in the manufacturing industry have contributed to a rise in hand motor dysfunction, negatively affecting both health and work efficiency. While rigid hand exoskeleton robots are effective, they are often heavy and may cause secondary injuries. In contrast, soft hand exoskeleton robots demonstrate significant potential as tools for injury prevention and assistance. This paper presents a hand-wearable pneumatic soft robot designed to assist in daily hand activities and prevent muscle atrophy. The developed soft actuator features a nested structure with uniformly distributed cross-sectional shapes of the internal pneumatic chamber. A constraining shell, made of materials with a different elastic modulus than the main structure, is placed around the pneumatic chamber to limit radial expansion. Based on the general structural parameters of the cross-sectional shape, a physical model was established to simulate bending conditions. The actuator prototype was fabricated using a multistep casting method. During experiments, at an air pressure of 43 kPa, the actuator achieved an average bending angle of \\(260 \pm 5^\circ \\) and an average output force of \\(6.0 \pm 0.1 \\, \text{N} \\). The soft actuator was integrated into a wearable hand robot for further testing. Results demonstrate that it effectively supports finger flexion and object grasping while helping to reduce muscle fatigue.

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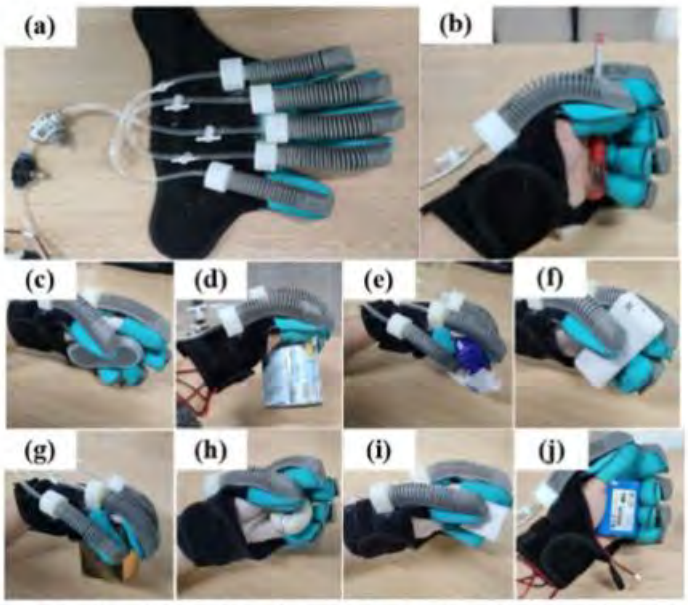

Fig. 11 Pneumatic soft exoskeleton robot and grasping demonstration. **a** Soft pneumatic exoskeleton robot. **b** Neutral pen. **c** Mouse. **d** Food can. **e** Tissue. **f** Remote control. **g** Carton. **h** Headset. **i** Charger head. **j** Lithium battery

How NOKOV Contributes to the Research

The flexible bending sensor comprises two offset flexible capacitors that measure the differential capacitance between them, with the output voltage corresponding to angular displacement. To calibrate the differential capacitive bending sensor, the NOKOV (Mars2H, Beijing Nokov Science and Technology Co. Ltd.) optical motion capture system is employed to acquire the spatial coordinates of three fixed points on the side of the soft actuator, from which the actual bending angle is derived. Reflective markers are affixed to the side of the actuator, and their positions are captured using an optical lens to approximate the actuator's bending state. During the experiment, the air pressure within the pneumatic chamber of the soft actuator is incrementally increased to achieve maximum bending, and the corresponding output voltage is recorded. The sensor exhibits a quiescent state voltage of approximately 80 mV, representing the bias voltage.

Citation Lv Y, Geng Z, Wu H, et al. Design and experimentation of the nested pneumatic soft actuator for hand exoskeleton[J]. Journal of Engineering and Applied Science, 2025, 72(1): 129.

Link

https://ev.publinks.top/app/doc/?docid=cpx_7e84659a198bc96ff9bM7a761017816329&pageSize=100&index=1&searchId=7ebec52ae2764d61b26d911bfa3b6ce8&resultsCount=2168&usageZone=resultslist&usageOrigin=searchresults&searchType=Quick

Design and kinematics of a novel rigid-flexible coupling hybrid robot for aeroengine blades in situ repair

Abstract

Purpose:This paper aims to present the mechanical design and kinematics of a novel rigid-flexible coupling hybrid robot to develop a promising aeroengine blades in situ repair technology.Design/methodology/approach:According to requirements analysis, a novel rigid-flexible coupling hybrid robot is proposed by combining a three degrees of freedom (DOF) parallel mechanism with a flexible continuum section. Then the kinematics models of both parallel mechanism and flexible continuum section are derived respectively. Finally, based on equivalent joint method, a two-step numerical iterative inverse kinematics algorithm is proposed for the whole robot: (1) the flexible continuum section is equivalently transformed to a 2-DOF spherical joint, thus the approximate analytical inverse kinematic solution can be obtained; (2) the accurate solution is derived by an iterative derivation of both parallel mechanism and flexible continuum section.Findings:To verify structure scheme and the proposed kinematics modeling method, numerical simulations and prototype experiments are implemented. The results show that the proposed kinematics algorithm has sufficient accuracy and computational efficiency in the whole available workspace, that is end-effector position error and orientation error are less than 0.2 mm and 0.01° respectively, and computation time is less than 0.22s.Originality/value:A novel rigid-flexible coupling hybrid robot for aeroengine blades in situ repair is designed. A two-step numerical iterative inverse kinematics algorithm is proposed for this unique hybrid robots, which has good accuracy and computational efficiency.

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How NOKOV Contributes to the Research

A motion-capture system (Mars 1.3 HW, Beijing NOKOV Science & Technology Co. , Ltd, CN) was utilized to accurately measure the deflection of the actuator under these applied loads. Markers wereplaced on the actuator, enabling precise tracking and measurement of movements and deformations. The defection inthe negative y-direction was meticulously recorded, and theoverall stiffness (K) of the actuator was subsequently calcu.lated using equation (2), facilitating a direct comparison withsimulated predictions and enhancing the validity of the experimental findings.

Citation Wu M, Xu Y, Wang X, et al. Design and kinematics of a novel rigid-flexible coupling hybrid robot for aeroengine blades in situ repair[J]. Engineering Computations, 2024, 41(10): 2504-2533.

Link https://www.emerald.com/insight/content/doi/10.1108/ec-10-2023-0741/full/html

Design and locomotion characteristic analysis of a novel tensegrity hopping robot

Keywords

Analytical models, Surveillance, Biomimetics, Length measurement, Robot sensing systems, Electromagnets, Turning

Abstract

In consideration of the poor locomotion ability of most traditional tensegrity robot, a novel tensegrity hopping robot powered by push-pull electromagnets was proposed with better locomotivity. It is able to conduct stable consecutive progressing action and turning action through hopping. This paper covers the structural design, theoretical modeling of the robot' s hopping process, as well as its self-righting analysis, simulation and experimental verification. The average moving speed and relative moving speed were measured to be 0.334m/s and 0.641 body length/s respectively, which obviously surpass the general moving ability of most traditional tensegrity robot. In addition, the robot was also validated to have good self-righting characteristic for stable consecutive hopping. Thus this robot can be potentially applied for search, rescue, detection, etc. in outdoor and unstructured environment.

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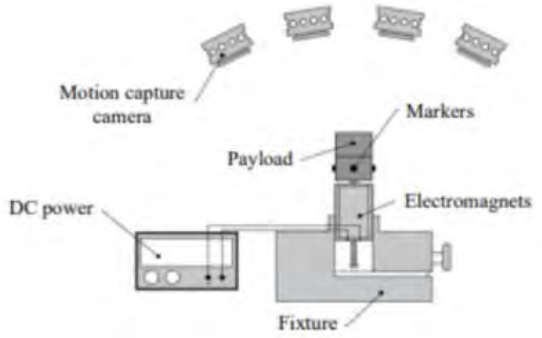

Figure 5. The experimental setup of electromagnet's thrust test.

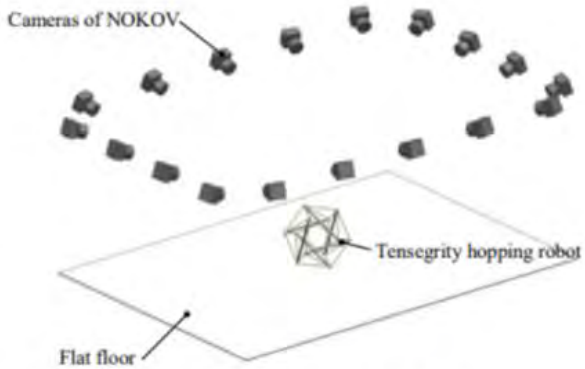

Figure 9. The experimental scene of robot's hopping experiment.

How NOKOV Contributes to the Research

Figure 5shows the experimental setup of electromagnet's thrust test. The payload consists of 1\~2 steel mass block, the mass of single mass block and the armature are0.4744kgand 0.1415kgrespectively. Besides, the values of turns per coil N, cross-sectional area of magnetic circuit Sand maximum gas length δmaxare 845, 176.71mm2and 60mm respectively.The armature's movement was recorded by the NOKOV motion capture system with a sampling frequency of 200Hz.

Citation Mo J, Gao C, Fang H, et al. Design and locomotion characteristic analysis of a novel tensegrity hopping robot[C]//2023 IEEE International Conference on Robotics and Biomimetics (ROBIO). IEEE, 2023: 1-8.

Link https://ieeexplore.ieee.org/abstract/document/10354708

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Design and locomotion characteristic analysis of two kinds of tensegrity hopping robots

Abstract

This study proposed two kinds of tensegrity hopping robots, which were actuated by push-pull electromagnets and servo motors, respectively. Both tensegrity robots are able to conduct stable and consecutive hopping actions. This paper covers the robots' structural designs, theoretical modeling of the hopping actuators, and detailed analysis of the robot's self-righting properties, all of which are validated by corresponding experimental and simulational results. The first hopping robot could hop forward at an average speed of 0.641 body length/s. Although the second robot has a lower moving speed of 0.237 body length/s, its average jumping height of 0.301 m is nearly 2.5 times higher than that of the first robot. Then compared with other tensegrity rolling robots, the proposed two robots show obvious advantages in locomotion performance over their counterparts. Therefore, the proposed robots can have large potential in many fields such as space exploration, urban search, military surveillance, etc.

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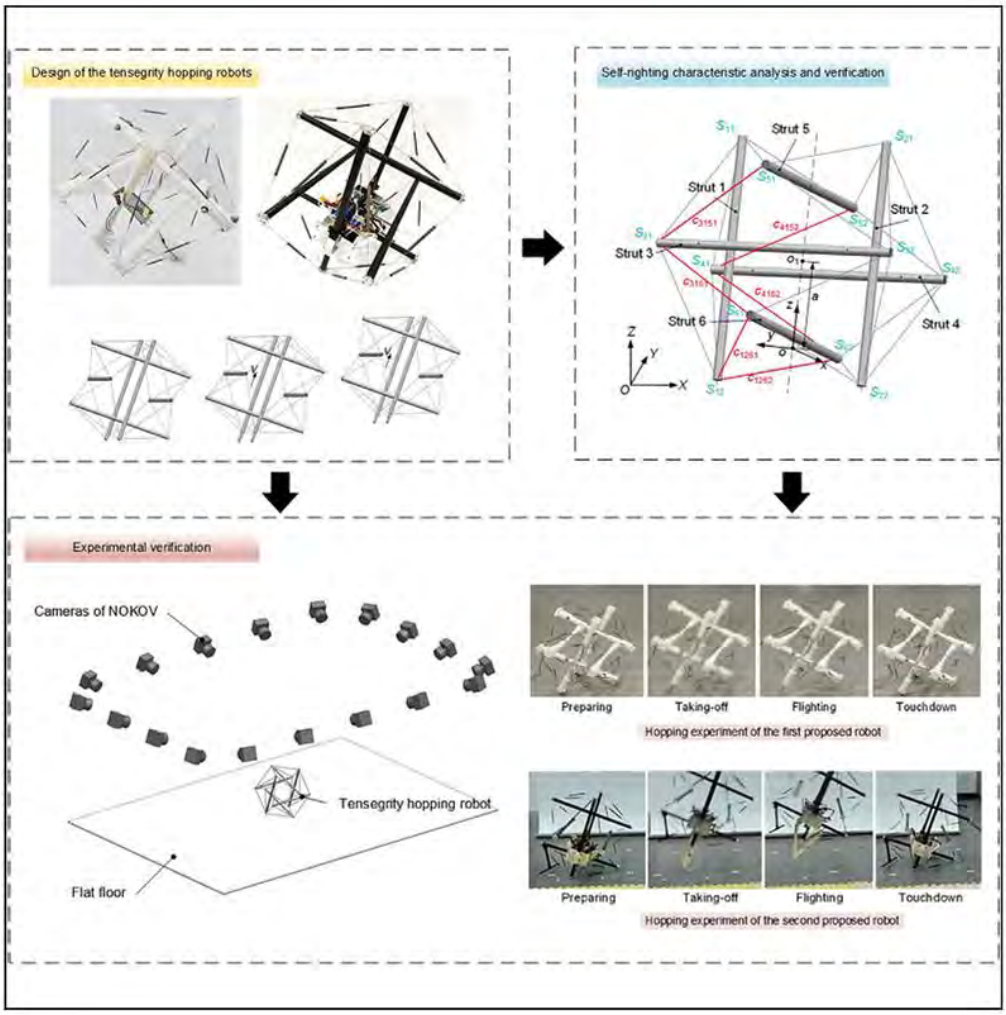

How NOKOV Contributes to the Research

Similarly, the experiment of the 5-bar mechanism aimed to measure its thrust property and validate the rationality of Equation 7 proposed in the last part. Figure 8 shows the experimental setup of the 5-bar mechanism's thrust test. The applied mass block payload was kept the same with the experiment of the electromagnet, and the mass of the 5-bar mechanism is 1.012 kg. In addition, the 5-bar mechanism's movement was also recorded by NOKOV with the same sampling frequency of 200 Hz.

Citation Jixue Mo, Hao Fang, Qingkai Yang,Design and locomotion characteristic analysis of two kinds of tensegrity hopping robots,iScience,Volume 27, Issue 3,2024,109226,ISSN 2589-0042, https://doi.org/10.1016/j.isci.2024.109226.

Link https://www.sciencedirect.com/science/article/pii/S2589004224004474

Design and statics model of an extensible hybrid-driven continuum robot with variable stiffness

Keywords

Extensible continuum manipulator, Variable stiffness, Hybrid-driven, Statics model

Abstract

Large workspace, variable stiffness, and accurate positioning are crucial indicators for enhancing the adaptability and reliability of continuum manipulators in operation tasks. Many structural design approaches only consider one of the extensible or variable stiffness features of continuum manipulators. The statics model needs to be constantly improved in accordance with the design structure to enhance position precision. This paper designed an extensible and variable stiffness continuum manipulator based on a helical structure combined with soft pneumatic actuators (SPAs) to improve both the ability of flexibility and payload capacity in confined environments. It is significant to remark that we have established a hybrid-driven statics model that considers the influence of tendon path, friction, and stiffness gain on the precision of the endpoint. Using the fourth-order Runge-Kutta method in conjunction with the shooting method, we have determined the shape of the manipulator based on a known value of the force sensor. The stiffness of the continuum manipulator is altered by generating antagonistic forces through pressurization of the soft actuators under the constraint of the driving tendons. Then, we constructed a prototype of an extensible and variable stiffness continuum manipulator to verify the accuracy of the statics model. Experimental results demonstrate a stiffness variation factor of 9 times, with a length range of 230 mm ~ 340 mm. The relative accuracy of the endpoint is 2.29 % calculated by the established statics model. The proposed design can lay the foundation for the execution of diverse tasks in a confined environment.

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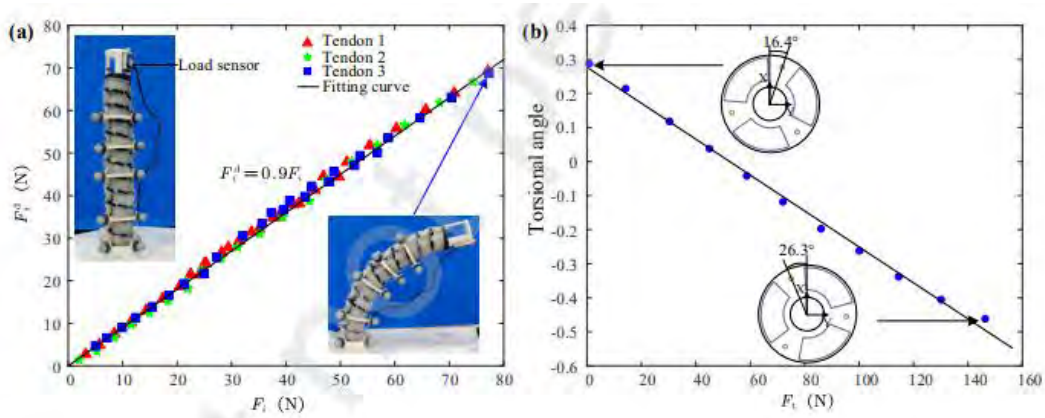

Fig. 5. Feature properties of backbone. (a) Proximal force and distal force in different tendons. (b) Torsion angle under pulling force of tendons.

How NOKOV Contributes to the Research

where represents the endpoint position of the manipulator calculated by the statics model. represents the endpoint position of the manipulator measured by the motion capture system (developed by Beijing NOKOV Science & Technology Co., Ltd., equipped with eight Mars 2H lenses distributed around the manipulator).

Citation Wang P, Zang J, Dong Z, et al. Design and statics model of an extensible hybrid-driven continuum robot with variable stiffness[J]. Sensors and Actuators A: Physical, 2025, 384: 116177.

Link https://www.sciencedirect.com/science/article/abs/pii/S0924424724011713

Design of a Bio-Inspired Stiffness Controllable Continuum Robot for Object Grasping and Moving

Keywords

Continuum robot (CR), stiffness control, object coiling, bio-inspired robot, rigid-flexible coupling

Abstract

Continuum robots (CRs) possess better compliance than rigid manipulators. However, existing CRs suffer from difficulties in manipulating objects for the conflicting needs of high stiffness and flexibility. This letter proposes an elephant trunk-inspired CR for grasping and moving objects. The CR features a deformation mechanism based on coupling rigid discs and flexible elastic rods and a stiffness modulation mechanism (SMM) with a force amplification function. The SMM decouples the CR's stiffness adjustment from bending motion, achieving flexible control capabilities. The SMM uses a stiffness coding strategy (SCS) to adjust stiffness according to task requirements to improve grasp performance while maintaining flexibility. We established the robot's kinematics, friction, and coiling models, designed a control method to coil around and move objects, and simulated the robot's end position-pose space and object size-pose space. We designed a robot prototype and conducted various experiments. Results showed that the robot achieved free movement in randomly generated configurations, coiled around and moved various objects with a path deviation of less than 8.5%, increased stiffness to 206%, and increased grasp force by 31%, demonstrating its potential in real applications.

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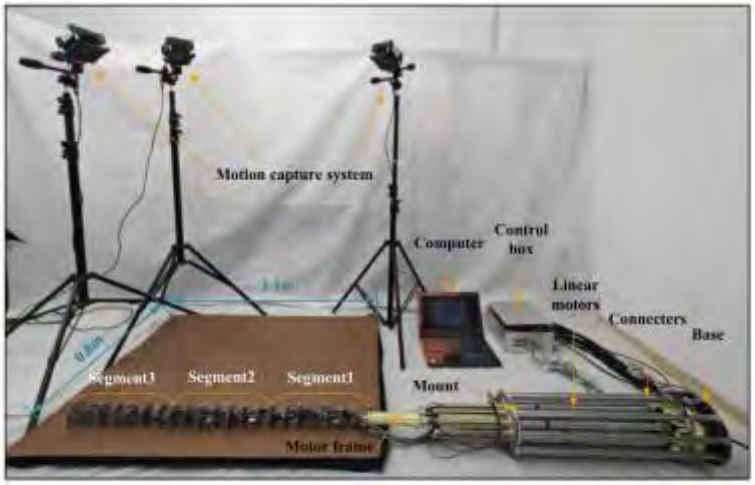

Fig. 7. Prototype of the CR and experimental platform.

How NOKOV Contributes to the Research

We built an experiment alplatform for experiments. A motion capture system (MCS) from Nokov Science & Technology Co. , Ltd was used to record the positions of the constraint discs during the movement of the CR,capturing its overall posture and shape. The infrared camera of the MCS has a resolution of 2048×1088 and 2.2 million pixels,providing sub-millimeter measurement accuracy. The MCS was also utilized to detect the position of the grasped object in real-time. The computer could send the control commands to the control box to realize the robot's control.

Citation Zhang J, Chen H, Li Y, et al. Design of a Bio-Inspired Stiffness Controllable Continuum Robot for Object Grasping and Moving[J]. IEEE Robotics and Automation Letters, 2025.

Link https://ieeexplore.ieee.org/document/10870121

Design of a Self-Locking Component for McKibben Muscle Back-Stretchablility

Keywords

McKibben Artificial Muscles, Self-locking, An-tagonist muscle, Bionics Robotics

Abstract

McKibben muscles are widely utilised in biorobotics due to their high contraction ratio, remarkable power-to-weight ratio, and resemblance to skeletal muscles. However, the original design, constrained by the braided net, prevents elongation (back-stretchability) when inactive. This limitation means that McKibben muscles lack an essential characteristic of skeleton muscles: the ability to elongate when relaxed. This shortage results in the fact that when the McKibben muscles are used to mimic the antagonist muscle drives, they must be installed loosely (the McKibben muscle will sag while inactivated because the length of the McKibben muscle should be longer than the distance of two fixed points) to ensure the realization of antagonistic muscle movements. However, this compromise inevitably results in the waste of the contraction length of the McKibben muscle, leading to a reduction in the range of motion of the robot joints and the response speed. This paper proposed a Self-locking Component (SLC) enabling back-stretchability of McKibben muscle. When the McKibben muscle is inactivated, the component can contract with different stiffness springs to allow for elongation. Whenever the McKibben muscle with SLC is activated, the SLC will be locked with the McKibben muscle contracting. The elongation-load curve and max tensile force were tested. The results show a strong linear relationship with a max tensile force 50 N. Proposed self-locking component can achieve the self-locking and back-stretchable function.

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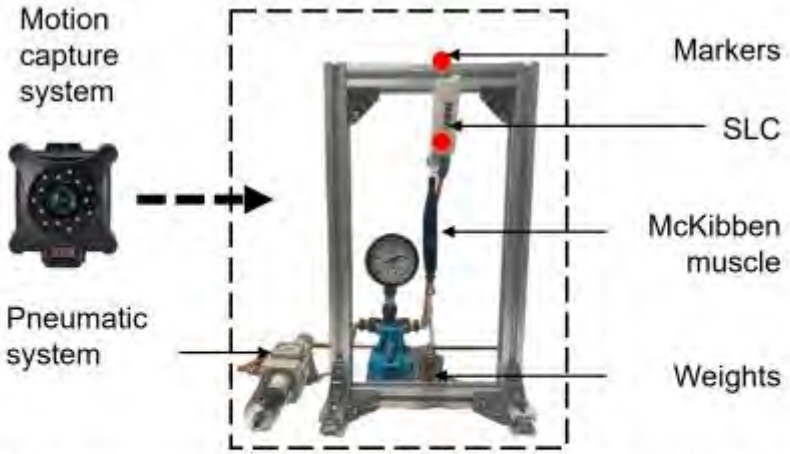

Fig. 5: The experiment setup: the SLC is attached to a McKibben Muscle with a pneumatic system . The pneumatic system is consist of a compressor, a manual regulatir, switching values, connectors and tubes. The motion capture system is used to measure the elongation of the SLC.It is a 3D capture system to measure the distance between two markers.

How NOKOV Contributes to the Research

The NOKOV Motion Capture System (Beijing NOKOV Science and Technology Co., Ltd.) was employed to capture the movement of theSLC. Two markers were used, one marker was affixed to the testbed, and another marker was affixed to the component itself.

Citation Mao S, Zhou Z, Villarroel M, et al. Design of a Self-Locking Component for McKibben Muscle Back-Stretchablility[C]//2024 17th International Convention on Rehabilitation Engineering and Assistive Technology (i-CREATe). IEEE, 2024: 1-5.

Link https://ieeexplore.ieee.org/abstract/document/10776187

Design of hybrid variable stiffness human–computer interaction contact unit module based on granular jamming

Keywords

Granular jamming, Variable stiffness, Human – computer interaction, Human – machine compatibility

Abstract

Existing rehabilitation exoskeleton robots suffer from poor compatibility with the human limb coupling method, large internal power loss, and poor wearable performance, which seriously affect the rehabilitation ability of these robots. Therefore, this study proposes a variable stiffness human–computer interaction contact unit module (VSHCUM) based on the granular jamming mechanism. It is characterized by a double-layer chamber structure: the inner layer is a granular chamber, and the outer layer is an air chamber. The interaction force is transmitted by embedding a rigid support in the inner layer. Unlike the common flexible-belt interactive contact unit, when the exoskeleton is bound to the patient's limb, VSHCUM can realize adaptive fitting of the patient's limb shape using the pressure change in the double-chamber structure. Simultaneously, by adjusting the vacuum level of the granular chamber, the stiffness of the interactive contact unit can be adjusted by a factor of more than five, and the internal work loss caused by self-pulling deformation during the auxiliary force transfer process can be reduced.

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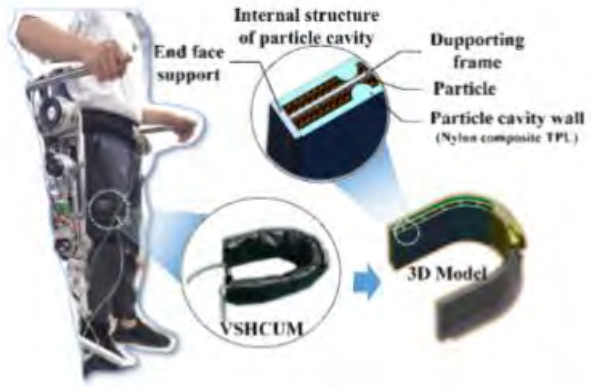

Fig. 2. Variable stiffness human–computer interaction contact unit module.

How NOKOV Contributes to the Research

4.1. Tracking experiment of traction motion process
Based on the rehabilitation exoskeleton robot platform developed in the laboratory, the exoskeleton traction of human lower-limb movement under passive rehabilitation training using flexible straps and VSHCUM was tracked. The subjects were connected to the exoskeleton through a human-computer interaction contact unit, The exoskeleton passively drives the lower limbs of the human body through an inter.active contact unit. The movement of the exoskeleton and lower limbs of the human body was tracked, and the passive motion tracking error was recorded when using flexible strap and VSHCUM contact units. ANOKOV visual motion capture system was used for motion tracking.

Citation Gao C, Wang C, Zhang J, et al. Design of Hybrid Variable Stiffness Human–Computer Interaction Contact Unit Module Based on Granular Jamming[J]. Chinese Journal of Mechanical Engineering, 2025: 100025.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001625198600001

Design, kinematics and validation of a multisection continuum robot connected by offset cross revolute joints

Keywords

Continuum robot, Offset cross revolute joint, Structure design, Kinematics analysis, Experimental validation

Abstract

Continuum robots have increasingly attracted attentions owing to inherent compliance and dexterity, which can be utilized for accessing unstructured and confined space. A novel multisection continuum robot connected by unique rigid-compliant combined offset cross revolute joints is presented in this paper, which has high length/diameter radio, well bending capacity and appropriate torsional stiffness. Then, a multilevel kinematic model is established, i.e., the mappings among actuator space, joint space and task space. Particularly, an advanced combined joint-end inverse kinematics algorithm is proposed to effectively reduce errors from approximation of the traditional FABRIK method, which is verified by several numerical simulations. Finally, to further verify structural design and kinematic models, a prototype of the continuum robot is established. Experimental results show that the proposed combined joint-end inverse kinematics algorithm has higher accuracy than traditional FABRIK method, and the continuum robot has well motion performance and load capacity.

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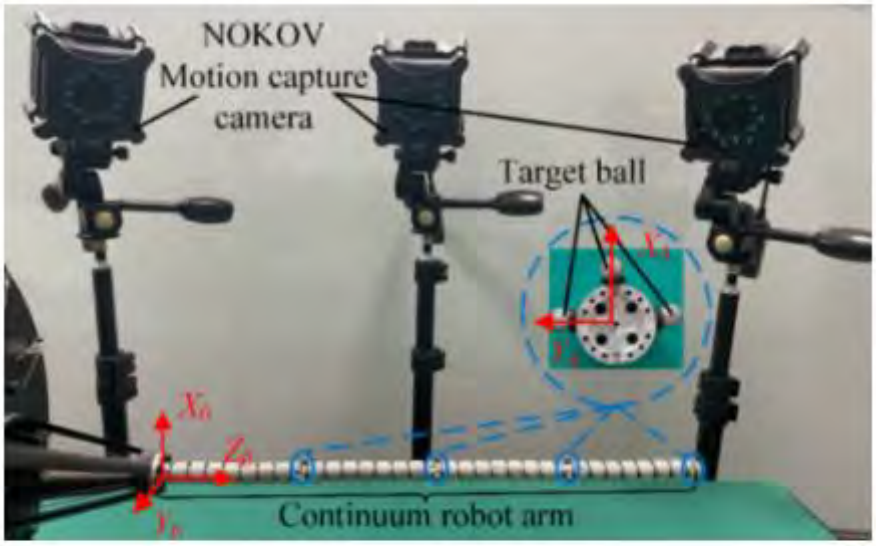

Fig. 19 Measurement scheme based on motion capture system

How NOKOV Contributes to the Research

The NOKOV motion capture system, i.e., Mars 1.3H cameras with maximum error of ± 0.2 mm is utilized to measure configurations of the continuum robot arm. It is notable that in order to simultaneously obtain positions and orientations, three target balls are installed on the end of each section, as shown in Fig. 19. Then, by defining a local coordinate system, end position and orientation can be derived based on the captured positions of the three target balls.

Citation Wang X, Li G, Wu M, et al. Design, kinematics and validation of a multisection continuum robot connected by offset cross revolute joints[J]. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2025, 47(7): 351.

Link https://link.springer.com/article/10.1007/s40430-025-05670-2

Design, Modeling, and Experimental Validation of a Bio-Inspired Rigid-Flexible Continuum Robot Driven by Flexible Shaft Tension-Torsion Synergy

Keywords

octopus arm inspired actuation, continuum robot, rigid–flexible hybrid robot, tensile–torsional synergistic actuation, kinetostatic modeling, flexible shafts

Abstract

This paper presents a bio-inspired rigid–flexible continuum robot driven by flexible shaft tension–torsion synergy, tackling the trade-off between actuation complexity and flexibility in continuum robots. Inspired by the muscular arrangement of octopus arms, enabling versatile multi-degree-of-freedom (DoF) movements, the robot achieves 6-DoF motion and 1-DoF gripper opening and closing movement with only six flexible shafts, simplifying actuation while boosting dexterity. A comprehensive kinetostatic model, grounded in Cosserat rod theory, is developed; this model explicitly incorporates the coupling between the spinal rods and flexible shafts, the distributed gravitational effects of spacer disks, and friction within the guide tubes. Experimental validation using a physical prototype reveals that accounting for spacer disk gravity diminishes the maximum shape prediction error from 20.56% to 0.60% relative to the robot's total length. Furthermore, shape perception experiments under no-load and 200 g load conditions show average errors of less than 2.01% and 2.61%, respectively. Performance assessments of the distal rigid joint showcased significant dexterity, including a 53° grasping range, 360° continuous rotation, and a pitching range from −40° to +45°. Successful obstacle avoidance and long-distance target reaching experiments further demonstrate the robot's effectiveness, highlighting its potential for applications in medical and industrial fields.

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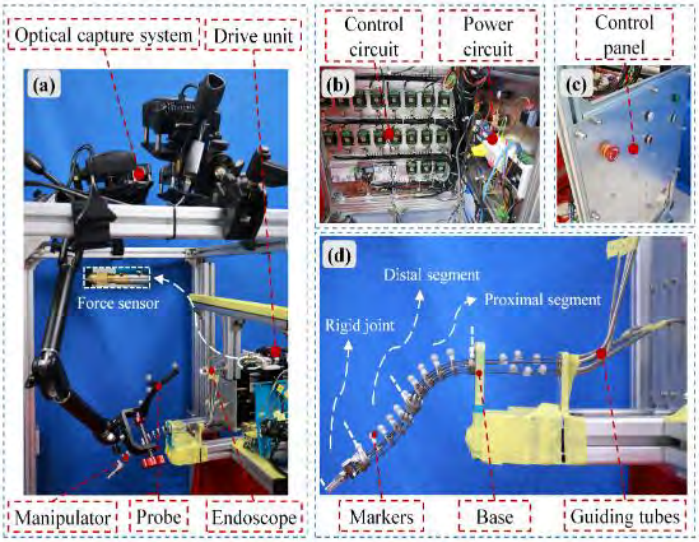

Figure 5. Prototype experimental system of the bio-inspired rigid–flexible continuum robot: (a) Overview of the experimental setup. (b) Physical layout of the control and power circuits. (c) Control panel for system operation. (d) Physical prototype of the manipulator.

How NOKOV Contributes to the Research

To verify the kinetostatic model of the bio-inspired rigid–flexible continuum robot, a prototype experimental system was built, as shown in Figure 5. The system mainly includes: power circuits, control circuits, an infrared motion capture system, drive units, a manipulator, and an endoscope. To measure the position data of the manipulator in space, a NOKOV optical 3D motion capture system was used, consisting of four infrared motion capture cameras (NOKOV, Beijing, China), one switch (NOKOV, Shenzhen, China), reflective markers, and a motion capture workstation. The motion capture cameras can achieve a maximum resolution of 1280 × 1024 with a frame rate of 240 FPS, and the 3D precision is ±0.2 mm. A handheld probe (NOKOV, Beijing, China) is connected to the motion capture system via a linkage bracket for precise measurement of small-scale structures. In the drive unit, three servo motors (Techrobots, Shenzhen, China) provide torsional driving force for the rigid joints, while six servo motors drive the flexible joints through tensile force. To obtain the tensile force data of the flexible shafts, six force sensors (Ryder, Shenzhen, China) are fixed to the motor output shafts through the intermediate modules. Reflective markers with a diameter of 6 mm are attached to the top of the manipulator's spacer disks, with a total of 11 markers used to capture the manipulator's shape data during the experiment.

Citation Dong J, Liu Q, Li P, et al. Design, Modeling, and Experimental Validation of a Bio-Inspired Rigid–Flexible Continuum Robot Driven by Flexible Shaft Tension–Torsion Synergy[J]. Biomimetics, 2025, 10(5): 301.

Link https://www.mdpi.com/2313-7673/10/5/301

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DIH-Tele: Dexterous In-Hand Teleoperation Framework for Learning Multiobjects Manipulation With Tactile Sensing

Keywords

Dexterous manipulation, dexterous teleoperation, fine in-hand manipulation, imitation learning, tactile sensing

Abstract

In daily life, the human hand exhibits remarkable abilities, such as fine in-hand manipulation and multimodal sensing, which are crucial for complex tasks like multiobject manipulation. However, current robotic dexterous hands have not yet achieved this level of proficiency due to limitations in hardware, perception algorithms, control strategies, and data collection. In this work, we present a dexterous in-hand teleoperation framework, DIH-Tele, designed to enable such complex tasks. The framework includes the tactile dexterous hand (T-DexCo hand), an accurate dexterous teleoperation system, multimodal data collection, and an imitation learning algorithm based on discrete control space and fused training. The in-hand counting task is selected as a common example of multiobject manipulation, which involves counting a set of objects held in hand and selectively removing a specified number of them by in-hand manipulation. Our experimental results demonstrate that the DIH-Tele framework effectively leverages multimodal perception to perform multiobject manipulation tasks with a success rate approaching that of human teleoperation. Additionally, the learned fingertip behaviors are highly versatile, often utilizing every degree of freedom of the dexterous hand. Finally, ablation studies confirm the significant impact of multimodal perception and fused training on enhancing multiobject manipulation tasks.

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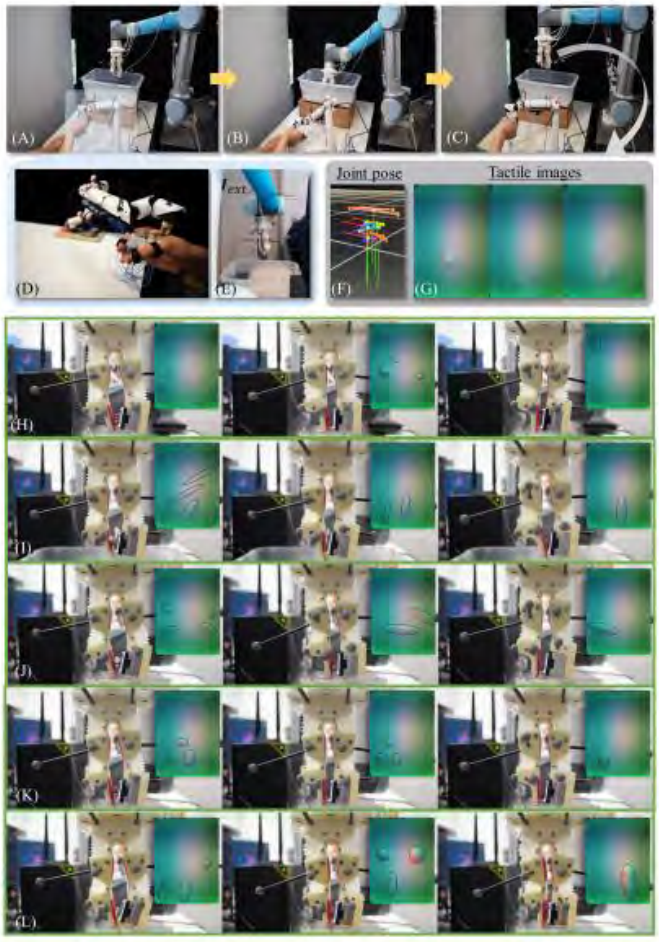

Fig. 8. System setup and experimental results. (a)–(c) Sequence of dexterous teleoperation. (a) Start stage. (b) Grasping from a pile of irregular stones. (c) Manipulation of objects. (d) User teleoperates to perform in-hand counting. (e) View from the human teleoperator's perspective. (f) Recorded rigid body poses of the T-DexCo hand links. (g) Recorded tactile images during manipulation. (h) Manipulating irregular stones (task 1). (i) Manipulating irregular pillars (task 3). (j) Manipulating pills (task 4). (k) Manipulating mixed irregular stones and pillars (task 5). (l) Manipulating mixed regular balls and pillars (task 6). .

How NOKOV Contributes to the Research

All experiments were conducted on the experimental platformshown in Fig.8(a)-(c).The platform consists ofthe teleoperationsystem, the T-DexCo hand, a UR5 robotic arm, a syringe pumpbox, and a motion capture system (comprising eight Nokov cameras).

Citation Huang J, Chen K, Zhou J, et al. Dih-tele: Dexterous in-hand teleoperation framework for learning multiobjects manipulation with tactile sensing[J]. IEEE/ASME Transactions on Mechatronics, 2025.

Link https://ieeexplore.ieee.org/document/10898061

Efficient RRT*-based Safety-Constrained Motion Planning for Continuum Robots in Dynamic Environments

Abstract

Continuum robots, characterized by their high flexibility and infinite degrees of freedom (DoFs), have gained prominence in applications such as minimally invasive surgery and hazardous environment exploration. However, the intrinsic complexity of continuum robots requires a significant amount of time for their motion planning, posing a hurdle to their practical implementation. To tackle these challenges, efficient motion planning methods such as Rapidly Exploring Random Trees (RRT) and its variant, RRT, have been employed. This paper introduces a unique RRT-based motion control method tailored for continuum robots. Our approach embeds safety constraints derived from the robots' posture states, facilitating autonomous navigation and obstacle avoidance in rapidly changing environments. Simulation results show efficient trajectory planning amidst multiple dynamic obstacles and provide a robust performance evaluation based on the generated postures. Finally, preliminary tests were conducted on a two-segment cable-driven continuum robot prototype, confirming the effectiveness of the proposed planning approach. This method is versatile and can be adapted and deployed for various types of continuum robots through parameter adjustments.

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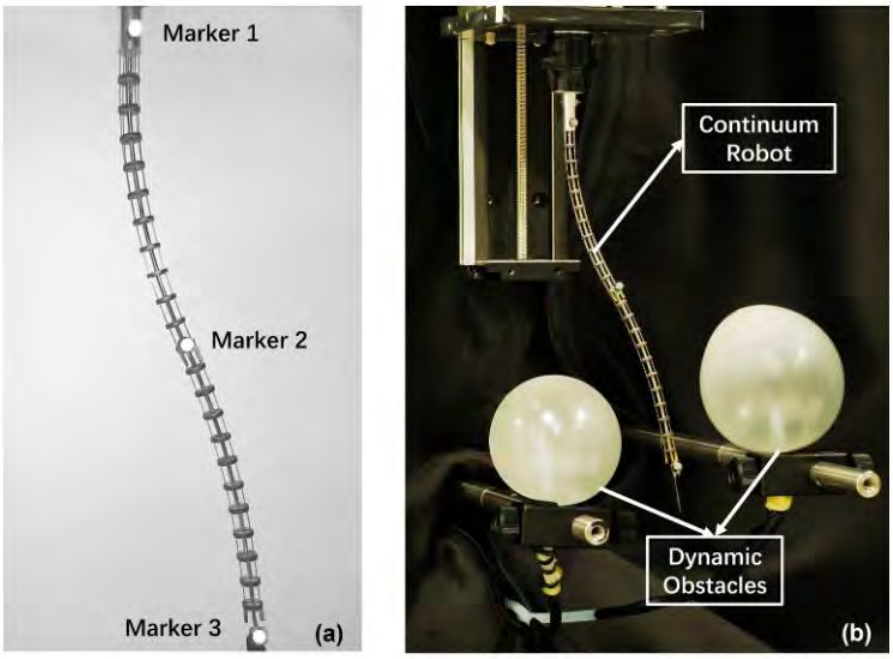

Fig. 1. The robot configuration. (a). Two-section continuum robot. (b). Real-world dynamic environment implementation.

How NOKOV Contributes to the Research

Employing five NOKOV® motion capture cameras with 0.3mm accuracy, we instrumented markers to track the robot's base, the proximal segment's tip, and the distal segment's end (see Fig. 1).

Citation P. Luo, S. Yao, Y. Yue, J. Wang, H. Yan and M. Q. . -H. Meng, "Efficient RRT-based Safety-Constrained Motion Planning for Continuum Robots in Dynamic Environments," 2024 IEEE International Conference on Robotics and Automation (ICRA), Yokohama, Japan, 2024, pp. 9328-9334, doi: 10.1109/ICRA57147.2024.10610309.

Link https://ieeexplore.ieee.org/abstract/document/10610309

Enabling sequential logic leveraging time delays of thin-walled soft matter

Abstract

Combinational logic is a common feature of modern engineered materials for general computation, but incorporating sequential logic is comparatively less advanced, which impedes further uses in environmental responses and adaptions. Sequential logic needs the history of the system outputs concomitantly with the present inputs, and we expect only one iteration of outputs and inputs for each operation. Thus, the main thrust of our research is to propose an original and general solution that utilizes the time delay effect of thin-walled soft matter inspired by origami structures to coordinate the work pace of the overall system. We create four basic sequential systems for ordered performance leveraging this device: a time delayer, a clock generator, a self-locking system (memory), and a pulse generator. Furthermore, we build five complex sequential systems based on the basic systems (a value assigner, a flip-flop, a shift register, a cycle shift register, and a counter). The novel contribution is making mechanical integrated circuit materials suitable for complex sequential control. Our approach is innovative, scalable to different sizes, and robust because it works only once after each input pulse. The inputs and outputs of our sequential systems can be force, light, or electricity for communication with other devices and general applicability.

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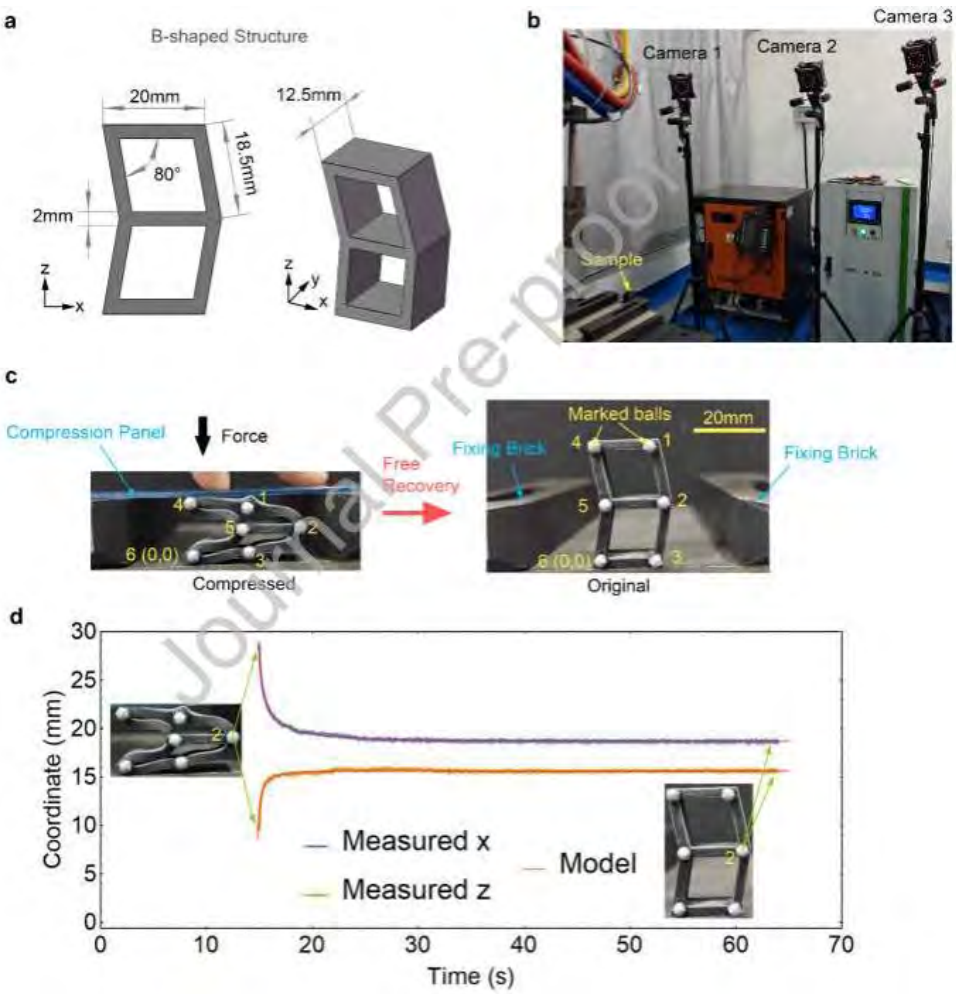

How NOKOV Contributes to the Research

Six balls were marked on the B-shaped structure to measure its deformation (Fig. 1). Three cameras of the motion capture system (NOKOV MARS2H, Beijing) emitted infrared radiation that was reflected by the marked balls and then received by the cameras.
A different high-speed camera system (FASTCAM Mini AX200 with interval between consecutive frames of 3.81 ms) was used in Figs. 2-8 for monitoring purposes since the laser or LED spots in these experiments may disturb the recognition of the NOKOV motion capture system.

Citation Yang N, Huang K, Qian Z, et al. Enabling sequential logic leveraging time delays of thin-walled soft matter[J]. Thin-Walled Structures, 2025, 209: 112968.

Link https://www.sciencedirect.com/science/article/abs/pii/S026382312500062X

Enhancing Continuum Robot Mobility: Design and Control with Integrated Dual Rotational DOFs

Abstract

Continuum robots, known for their compliance in unstructured environments, face limitations due to the lack of rotational degrees of freedom (DOFs) about the backbone. This prevents them from compensating undesired torsional deformation and performing 6-DOF control of the end-effector, thereby restricting their mobility. This paper presents a continuum robot with integrated dual rotational DOFs. One is integrated at the arm base to compensate for torsional deformation caused by external loads, while the other one, located at the arm tip, enables full 6-DOF control of the end-effector. To control the robot, a screw-theory-based kinematic model and a kinematic control framework are proposed to enable real-time, simultaneous control of the end-effector's position and orientation. Experimental results show that the arm base rotational joint can fully compensate for undesired torsional deformation caused by a 1000 g payload. Thanks to the arm tip's DOF and the proposed kinematic control framework, the robot's end-effector can maintain a constant orientation while achieving open-loop path-tracking errors of only 3.3% of the arm's length (930 mm), and successfully executing valve-closing tasks with coordinated 6-DOF motion, demonstrating the robot's potential for industrial maintenance, human-robot interaction, and confined-space manipulation.

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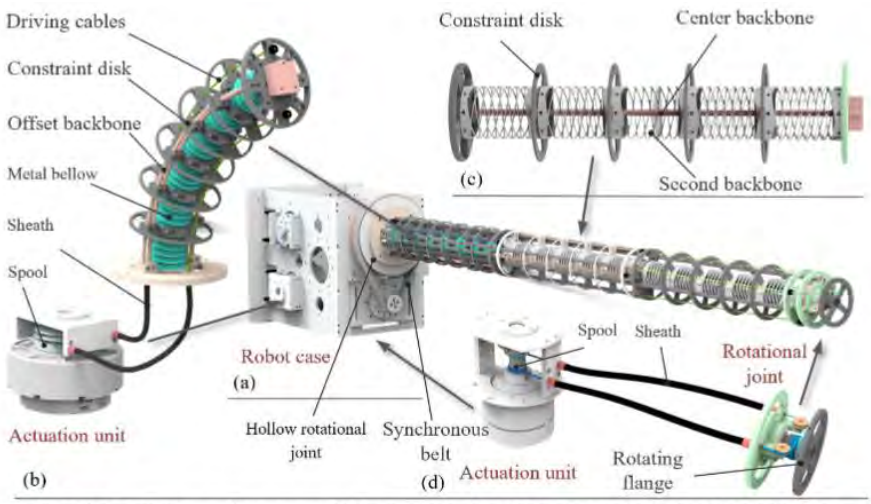

Fig. 1. Prototype Design. (a) Overall structure of the prototype. (b) Structure of Module 1. (c) Structures of Modules 2 and 3. (d) Rotational joint at the arm tip.

How NOKOV Contributes to the Research

To test the robot's mobility and its motion accuracy in task space, we conducted a path tracking experiment based on the kinematic control framework proposed in Section III-B. As shown in Fig. 5, we used the proposed kinematic control framework to have the robot track two paths: a rectangular path measuring 300×200 mm and a circular path with a diameter of 300 mm. Optical markers were attached to the arm tip, and a NOKOV motion capture system (Mars1.3H, 3D positioning accuracy ±0.2 mm) was used to record the actual path.

Citation P. Yuan, C. Sun, X. Chang, X. Zhang and R. Kang, "Enhancing Continuum Robot Mobility: Design and Control with Integrated Dual Rotational DOFs ," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 3287-3292, doi: 10.1109/IROS60139.2025.11247688.

Link https://ieeexplore.ieee.org/document/11247688

Flexible robotic hand harnesses large deformations for full-coverage human-like multimodal haptic perception

Abstract

Integrating human-level haptic perception into soft grippers promises safer robotic grasping and improved human–robot interaction. While visual-tactile sensors promise high perception resolution at low cost, they often sacrifice compliance to maintain optical stability, hindering non-planar contact perception. We present FlexiRay, a soft gripper that integrates visual-tactile sensing with the Fin Ray Effect to achieve high compliance, broad sensory coverage, and multimodal capability. Combining a multi-layered flexible substrate, an optimized multi-mirror optical system, and a decoupled deep learning framework, FlexiRay replicates five of the seven human tactile modalities, including force, contact location, texture, temperature, and proprioception, with a single camera. It achieves 0.17 N force accuracy, 0.96 mm spatial resolution, 0.24 mm proprioception accuracy, and 1.17 °C temperature accuracy while maintaining over 90% effective coverage. FlexiRay empowers compliant grasping, safe collaboration, and intelligent teleoperation, underscoring its potential to propel service robotics toward enhanced intelligence, safety, and real-world utility.

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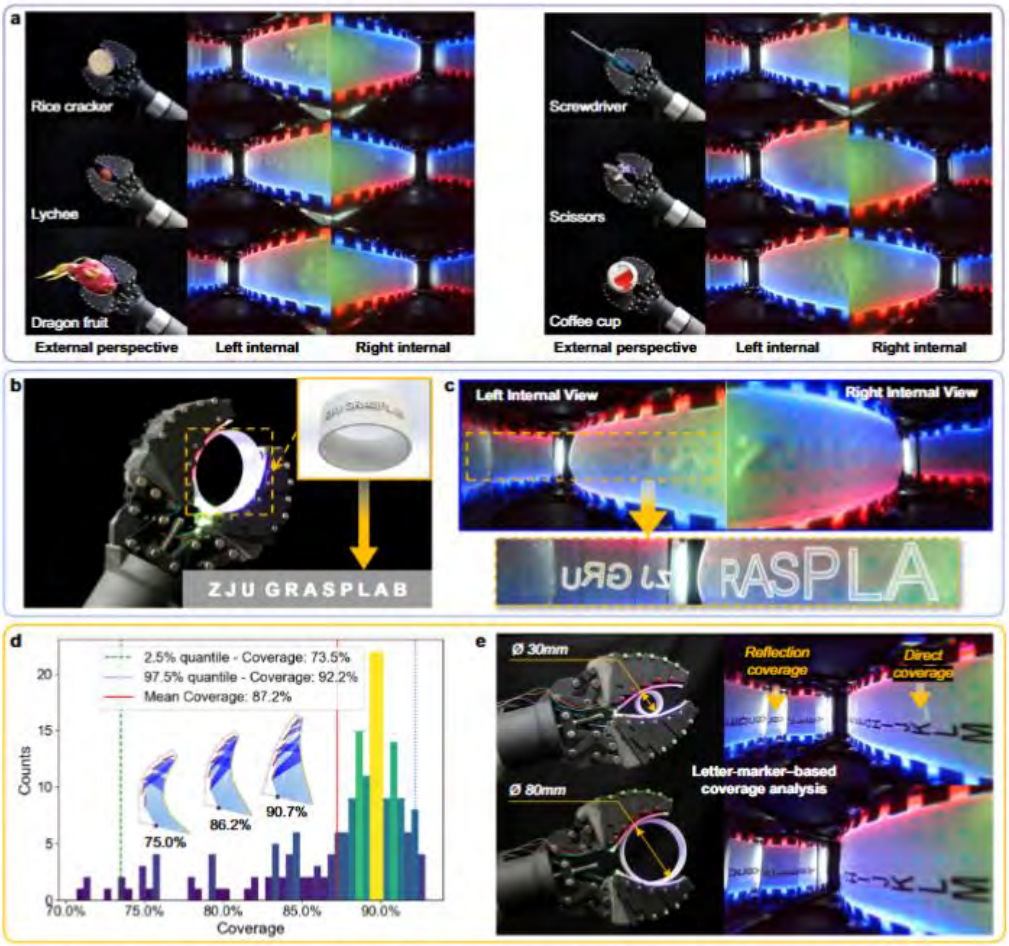

Fig. 4 | Texture detection performance and perceptual coverage of FlexiRay. **a** Raw internal images captured while gripping various objects. **b** 3D-printed text ring. **c** Internal raw image of the text ring grip, illustrating texture details captured by both direct and reflective sensing. **d** Distribution of perceptual coverage across 200 random deformation tests under varying loads. **e** Continuous alphabetic markers indicate the visible areas during ring-shaped grasps of different diameters, with the 30 mm and 80 mm rings shown as representative examples. Additional demonstrations are provided in the Supplementary Fig. 6.

How NOKOV Contributes to the Research

For experiments in the real world, a laptop with an AMD R5-5600U CPU and 16 gigabytes of memory is used for the optimization-based planner and the agent of ground actua-tors of the MARL-based decentralized planner. Two Jetson Orin Nano onboard computers with 8 gigabytes of memory are used for the two agents of aerial actuators of the MARL-based decentralized planner, respectively. The positional and geometric information of the moving plat-form, obstacle, and aerial actuators are measured by a NOKOV motion capture system. The length of variable-length cables is recorded by encoders.

Citation Wang Y, Guo H, Wu H, et al. Flexible robotic hand harnesses large deformations for full-coverage human-like multimodal haptic perception[J]. Nature Communications, 2025.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001598878500001

Human–Machine coupled modeling of mandibular musculoskeletal multibody system and its application in the designation of mandibular movement function trainer

Keywords

Dynamic optimization, Flexible multibody dynamics, Human – machine coupling, Musculoskeletal model, Trismus (limited mouth opening)

Abstract

Many patients suffering from oral and maxillofacial tumors present trismus in the six months following mandibulectomy. Traditional mandibular movement function trainers (MMFT) cannot fulfill patient-specific targeted training, but mandibular musculoskeletal modeling can reveal patient-specific muscle recruitment patterns. This study proposed a digital rehabilitation framework for patients via mandibular musculoskeletal simulations. A flexible MMFT consisting of a soft intraoral airbag and a cable-driven extraoral trainer was designed. A human–machine coupling model was established to estimate the patient-specific muscle activations. Here, the intraoral trainer was modeled as a force vector, and the extraoral trainer was discretized by the flexible cable elements via an arbitrary Lagrangian–Eulerian description. Dynamic optimizations were performed to determine the patient-specific auxiliary forces, and the obtained values were utilized to design a quantitative rehabilitation plan. The effectiveness of the MMFT at increasing the magnitude of mandibular opening was validated with in vitro measurements. Numerical predictions for eight patients demonstrated that the proposed rehabilitation framework could improve the patient's jaw opening magnitude by an average of 3.8 ± 2.0 mm, highlighting the importance of subject-specific musculoskeletal modeling in mandibular rehabilitation.

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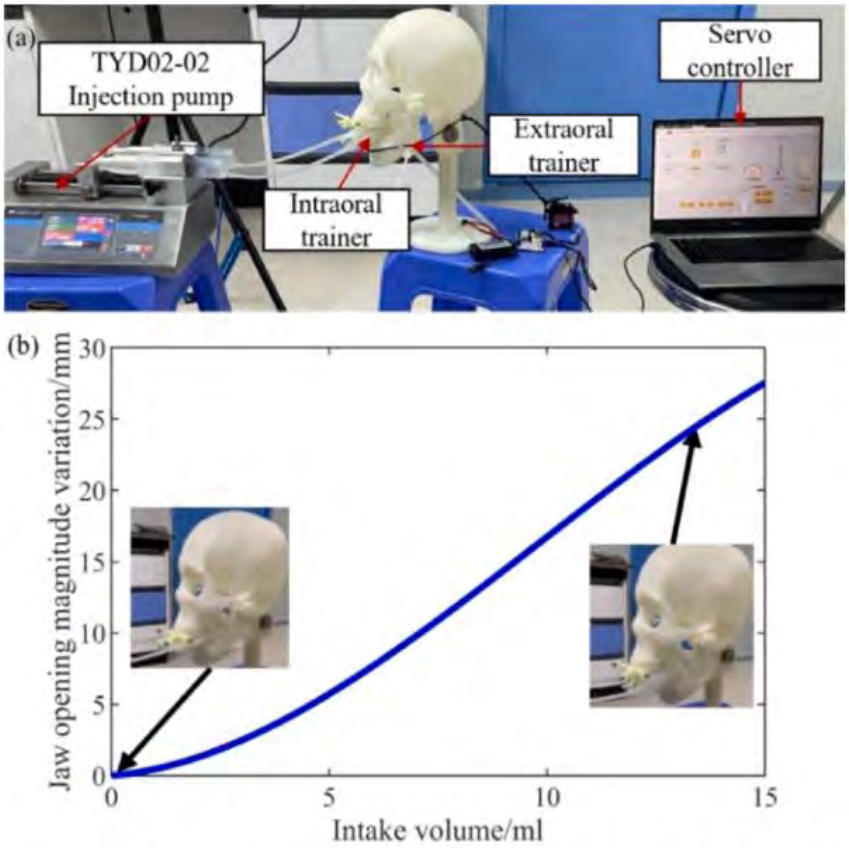

Fig. 9. MMFT verification. (a) *In vitro* experiment for verification of intraoral and extraoral MMFT. (b) The MMFT's effect on jaw opening magnitude.

How NOKOV Contributes to the Research

Functional validation of the MlMF'T was performed based on the dummy skull model with a 1 DOF mandibular bone (see Fig. 9fa)A motion capture systen with three infrared cameras (MARS 2S; Nokov Corp., Beiing, China) was established to measure the mandibular opening-closing kinematics. A jaw fork with three reflective markers was placed on the tpper and lower dentition of the invitro mandibular model. First, the relative positions of the forks and their attached maxillary/mandibular bones were registered usingC'T images.

Citation Wang X, Guo J, Wang J, et al. Human–Machine coupled modeling of mandibular musculoskeletal multibody system and its application in the designation of mandibular movement function trainer[J]. Mechanism and Machine Theory, 2024, 204: 105848.

Link https://www.sciencedirect.com/science/article/abs/pii/S0094114X24002751

Impact Resistance and Compliant Performances of Tensegrity-based Bionic Joint for Collaborative Robot

Keywords

Tensegrity, Bionic robot joint, Collaborative robot

Abstract

The most commonly adopted configuration of collaborative robot at present is multi-joint robotic arm, which is based on rigid modular joint. Compared with rigid joint, tensegrity-based bionic joint adapts to the requirement of collaborative robot better, because it has a great deal of advantages such as lightweight, flexibility, impact resistance and compliance which well fit robot in unstructured tasks and in human-computer interaction. Taking a wrist-inspired bionic joint as an example, impact resistance and compliance of tensegrity-based joint are studied. Experiments are carried out to study the performances of the joint under random shocks and being block at both stationary and waving states. The result shows that the tensegrity joint is able to return to the its neutral position or set trajectory after being struck or being blocked. The excellent features of impact resistance and compliance promise a potential future of tensegrity-based joint in collaborative robots.

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Figure 3: (a)experimental set up (b) prototype

How NOKOV Contributes to the Research

A motion capture system was used to record the motion of the joint.The detection accuracy of the NOKOV's optical motion capturesystem is 0.01mm, which met the requirements of the study. Asshown in the figure 3(a), the joint is placed within the observationrange of the motion capture system, and with the power supply andsignal line of the motors connected, the joint can be controlled bythe upper computer.

Citation Xie X, Wen Z. Impact Resistance and Compliant Performances of Tensegrity-Based Bionic Joint for Collaborative Robot[C]//Proceedings of the 2022 4th International Conference on Robotics, Intelligent Control and Artificial Intelligence. 2022: 70-74.

Link https://dl.acm.org/doi/10.1145/3584376.3584390

Kinematic analysis of a flexible surgical instrument for robot-assisted minimally invasive surgery

Keywords

Interaction force estimation; Passive lower limb exoskeleton; Level ground walking; Bilevel optimization

Abstract

Flexible surgical instruments can flexibly adjust their posture with a high degree of freedom, which makes them highly suitable for performing surgical tasks in narrow workspaces. However, redundant degrees of freedom increase their kinematic difficulty, which may cause redundant solutions, complex calculations, and low speeds. In this paper, a flexible surgical instrument is presented. The structural characteristics of this flexible instrument were explored in terms of force balance, it was concluded that the instrument had a constant curvature during bending. Based on this, the kinematics and inverse kinematics were solved via the geometric and Newton iteration methods, respectively. Our experiments showed that the proposed method for solving flexible instrument kinematics had high precision, a unique solution, and high speed; the instrument can be well controlled to perform refined operations. The proposed geometric method for solving the flexible instrument kinematics avoided the calculation of the Jacobian matrix, making it fast and capable of meeting the master-slave control requirement for real-time surgery. Furthermore, the proposed kinematics solution method is not limited by the mechanical structure, so it can be used for flexible instruments owning to its constant curvature bending.

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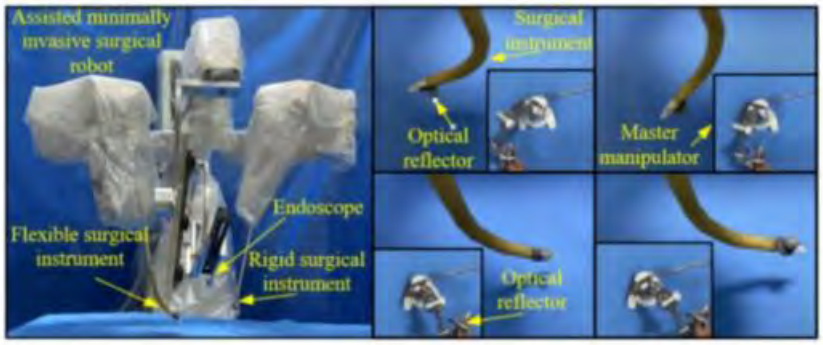

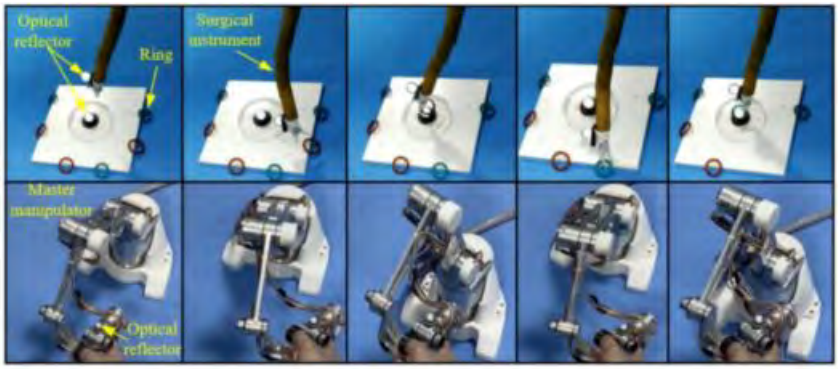

How NOKOV Contributes to the Research

To validate the performance of the instrument under refined manipulation, it was controlled to grasp rings in target locations, as shown in Fig. 10, and a motion capture system (NOKOVCo., China) was used to follow the master and slave during operation. Optical reflectors were fixed to the end effectors of the master manipulator and instruments to collect movement information. Fig. 11 shows the movement trajectories of the master manipulator and the instrument. Fig. 12 shows the trajectories of the master manipulator and instrument along the x, y, and z directions. The RMSE of the expected and actual trajectory of the flexible surgical instrument in the x, y, and z directions were 0.498, 0.399, and 0.051, respectively. The experimental results show that the instrument can be well controlled to perform refined operations and under master-slave operation.

Citation Feng M, Ni Z, Fu Y, et al. Kinematic analysis of a flexible surgical instrument for robot-assisted minimally invasive surgery[C]//2021 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2021: 12229-12235.

Link https://ieeexplore.ieee.org/abstract/document/9561634

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Kinematic and static analysis of a rigid-flexible hybrid robot with combined elastomer configuration of driving shafts and spinal rods

Keywords

rigid-flexible hybrid mechanism, tensile-torsional synergistic actuation, combined elastomer configuration, static analysis, flexible robots

Abstract

Flexible shafts, exhibiting excellent tensile and torsional transmission characteristics, serve as an ideal power transmission medium for the design of flexible continuum robots. This study introduces a novel rigid-flexible hybrid robotic mechanism employing six flexible shaft actuators to achieve seven degrees of freedom (DOFs). The design integrates a dual-segment flexible body with a single-segment rigid body. A comprehensive kinematic model was derived to describe the hybrid structure's motion. Concurrently, a static model was developed, incorporating driving forces, external loads, gravitational effects, and the combined elastic forces from the flexible driving shafts and spinal rods. Based on this static model, 182 combinations of flexible shaft pulling forces and distal loads were applied to control the robot's posture. Experimental results indicated that the maximum positional errors for the single- and dual-segment configurations were 2.67% and 5.97% of the manipulator length, respectively. The maximum root mean square error for spatial configuration repeatability is 0.4 and 5.1 mm for single- and dual-segment flexible robots, respectively. The kinematic and static models developed in this research accurately predict the spatial configuration of the flexible continuum robot, which features an integrated elastic arrangement of driving shafts and spinal rods, thereby facilitating rapid deployment in similar flexible robotic systems.

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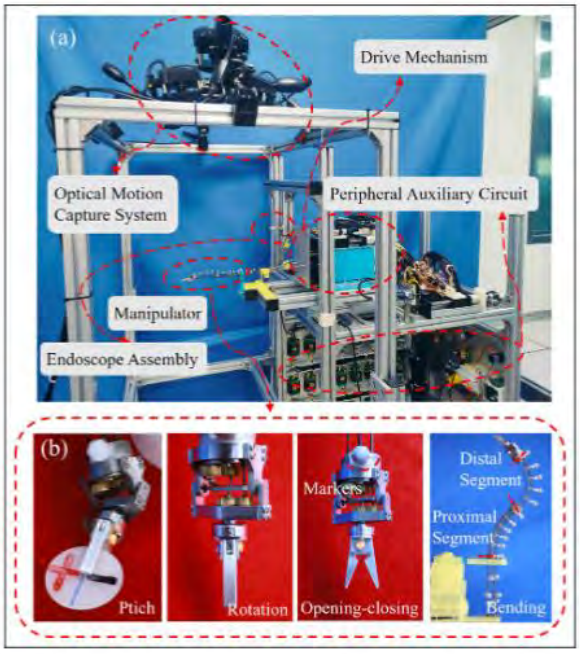

Figure 7. Experimental platform and functional demonstration of the rigid-flexible hybrid robot: (a) the overall experimental setup, comprising the drive mechanism, optical motion capture system, and the manipulator and (b) functional demonstration of the robot, showing the rigid joint performing pitch, rotation, and opening-closing motions, and the flexible joints performing multi-segment bending.

How NOKOV Contributes to the Research

Tension-compression force sensors(RDF-TM10, Ryder, China),which are fixed to the motor's output shaft, are used to measure the tension on the flexible shafts, while providing a comprehensive accuracy of 0.1% of full scale. An optical dynamic capture system is used to sense the postural information of the flexible continuum robot through identifying the position of the optical markers, which are placed at spacer disks along the elastic backbone. The optical dynamic capture system comprises four motion capture cameras (1280 x 1024 resolution, MARS1.3H, Nokov China), achieving a maximum frequency of 240 FPS and a positional accuracy of + 0.2 mm. At the beginning of motion capture experiments, the entire 3Dsystem will be calibrated in three motion capture aspects, including: determination of the coordinate origin, field sweeping, and error calculation. Then, the robot system will control the motors to drive flexible shafts for motion implementation.

Citation Dong J, Zhao X, Wang C, et al. Kinematic and static analysis of a rigid-flexible hybrid robot with combined elastomer configuration of driving shafts and spinal rods[J]. Advances in Mechanical Engineering, 2025, 17(11): 16878132251378307.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001609833800001

Kinematic Modeling and Control for an Elephant-Trunk Soft Manipulator Considering Hysteresis

Keywords

Kinematic model and control, soft manipulator, soft robotics

Abstract

Soft manipulators have been widely developed due to their manipulation safety, design versatility, and motion dexterity. However, accurate kinematic modeling and control of soft manipulators are still challenging due to the complex nonlinear hysteresis in their motion characteristics. This article presents the fabrication of an elephant-trunk-inspired soft manipulator (ESM) using pneumatic bellows actuators (PBAs) and proposes a kinematic modeling and control method considering hysteresis. The ESM contains three soft arms and a pneumatic claw, while each soft arm consists of four PBAs connected in parallel. The forward kinematics of the ESM are modeled using the piecewise constant curvature (PCC) method. The kinematic model of the ESM consists of three parts: actuator space, configuration space, and task space. To address the inability of the PCC method to characterize the nonlinearity of soft materials, the hysteresis of the PBA in the actuator space is modeled using the Prandtl–Ishlinskii model. The inverse kinematic model of the ESM is derived from its forward kinematic model, and on this basis, a feedforward controller is developed to achieve position control of the ESM. The positional workspace of the ESM is analyzed using the Monte Carlo method. The validity of the kinematic model is verified experimentally. Position control and application experiments are conducted to demonstrate the practical application of the ESM.

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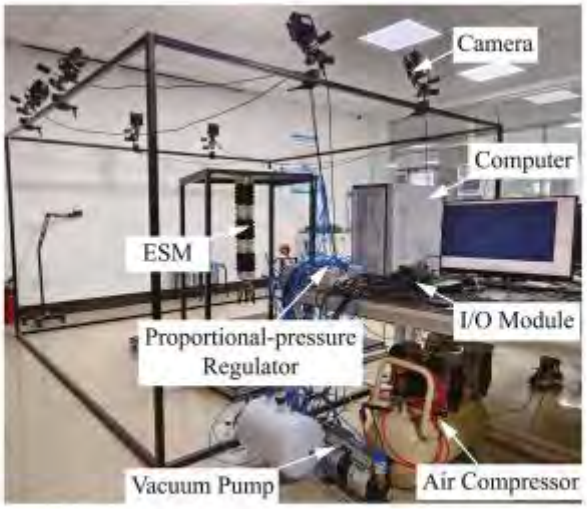

Fig. 2. Pneumatic experimental platform.

How NOKOV Contributes to the Research

The established pneumatic experimental platform containsthe following six parts (see Fig.2): 1) computer: CPU: Intel i9-12900KF; memory: 16 G; man-ufacturer: Asus; 2) I/O module: model number: PCIe-6363; manufacturer:National Instruments; 3) air compressor: model number: OTX-550X3; manufac-turer: Outstanding; 4) vacuum pump: model number: JBL-750; manufacturer:Jiabaoli; 5) proportional-pressure regulator: model number: VPPI-5L-3-G18-1V1H-S1D; manufacturer: Festo; 6) camera: model number: Mars 2H; manufacturer:NOKOV.

Citation Xiao H, Lai X, Meng Q, et al. Kinematic modeling and control for an elephant-trunk soft manipulator considering hysteresis[J]. IEEE Transactions on Industrial Informatics, 2024, 20(9): 11318-11328.

Link https://ieeexplore.ieee.org/abstract/document/10543006

Kinetostatics of Magnetic Captained Elastica Driven by Revolutional and Rotational Magnet

Keywords

Chained beam-constraint-model, kineto-static model, magnetic drive strategy, medical robot.

Abstract

Magnetic continuum robots (MCRs) hold considerable promise for medical applications, particularly in navigating the intricate and narrow lumens of the human body. However, accurately modeling their nonlinear large deformations, especially in nonuniform magnetic fields with bending angles exceeding 180°, poses a significant challenge. This research presents a theoretical framework for the magnetic captained elastica (MCE), which integrates magnetic dipole theory and the chained beam constraint model to effectively characterize the extreme deformations of permanent magnet-driven MCRs. The proposed kineto-static model is rigorously validated through finite element simulations and experimental testing. Two permanent magnet actuation strategies, revolutionary and rotational driving, are introduced to enhance precise deformation control, implemented via a specialized magnetic continuum robot navigation system. This system successfully demonstrates the MCE model's capability to transition between global large deformations and local small deformations, as evidenced by phantom experiments in gastric drug delivery and tracheal intubation. These findings underscore the model's accuracy and its significant potential for advancing clinical robotics.

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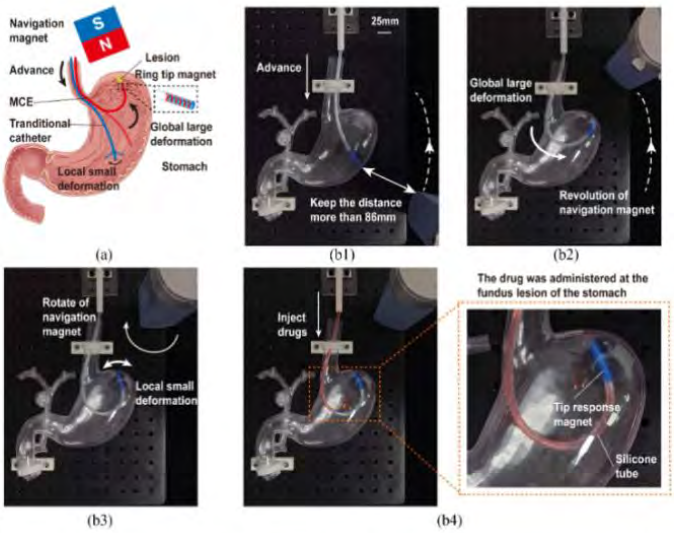

Fig. 7. MCE was applied to the gastric model for drug delivery work. (a) Schematic of the administration of drugs to gastric lesions. (b1)–(b4) Drug delivery experiments were performed on the stomach phantom using MCE.

How NOKOV Contributes to the Research

To analyze the deformation of MCE under the revolution drive strategy, the established nonlinear kinetostatic model was used for two different MCE specifications. To validate the model, an experimental platform was constructed, utilizing a motion capture camera (NOKOV Motion Capture, Mars4H, China) to measure the deformation of MCE under identical revolution drive parameters.

Citation Zhang Y, Song W, Li A, et al. Kinetostatics of Magnetic Captained Elastica Driven by Revolutional and Rotational Magnet[J]. IEEE/ASME Transactions on Mechatronics, 2025.

Link https://webofscience.clarivate.cn/wos/woscc/full-record/WOS:001582297800001

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Location encoding neural network-based posture estimation and vision-based implementation for continuum robots

Keywords

Deep learning, Visual perception, Continuum robot

Abstract

The capability of whole-body proprioception, e.g., pose estimation, is important for the control and interaction of continuum robots. However, existing pose estimation methods are often simplified through geometric assumptions, primarily due to constraints such as computational and sensor deployment costs. We propose an explicit posture estimation method through a neural network, and implement it using an embedded camera for vision-based proprioception. We design a continuous location encoding neural network (LENN) by encoding continuous locational information. The LENN can capture deformation from changes in internal texture observed by an integrated camera, and output pose information—both position and orientation—for any point along the robot backbone, rather than only discrete points. Compared with interpolation-based estimation using a reduced model, our method reduces single-point estimation error by 33.6%. Furthermore, a systematic evaluation of hardware configurations demonstrates that our prototype achieves sub-millimetre accuracy in shape estimation (0.383 mm) while maintaining real-time inference speeds below 12 ms per frame. By combining a learning-based approach with a simple mechanical design, our method leverages internal visual information to estimate the whole-body pose, providing an effective solution for accurate shape estimation in continuum robots.

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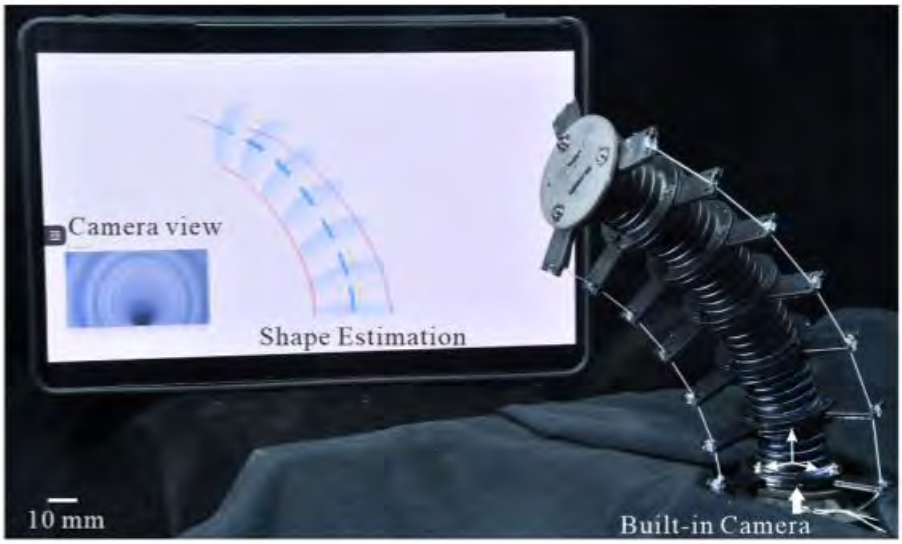

Fig. 1. Real-time vision-based shape estimation of a flexible continuum robot through images of the internal ridge features of the bellows. A camera is placed at the center bottom to capture the structure deformation of the backbone and a neural network is used to estimate the whole-body shape.

How NOKOV Contributes to the Research

Markers on the skeletons enable spatial tracking via an optical motion capture system (Mars4H, NOKOV) for validation, which provides a 3D accuracy of ±0.1 mm. A 60 FPS camera and an LED board are positioned at the base center of the hollow backbone, with four white LED beads providing illumination. Data and power cables exit through base openings. Since the camera reaches \~40°C during operation, the base is made of heat-resistant nylon (200°C) to prevent deformation that could alter the camera's viewing angle.

Citation Yong H, Wang J, Ding H, et al. Location encoding neural network-based posture estimation and vision-based implementation for continuum robots[J]. Science China Technological Sciences, 2026, 69(2): 1220302.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001682413600003

Locomotion control of a rigid-soft coupled snake robot in multiple environments

Keywords

Snake robot, Rigid–flexible coupled, Soft actuator, Motion gait analysis

Abstract

The versatile motion capability of snake robots offers themselves robust adaptability in varieties of challenging environments where traditional robots may be incapacitated. This study reports a novel flexible snake robot featuring a rigid–flexible coupling structure and multiple motion gaits. To better understand the robot's behavior, a bending model for the soft actuator is established. Furthermore, a dynamic model is developed to map the relationship between the input air pressure and joint torque, which is the model base for controlling the robot effectively. Based on the wave motion generated by the joint coupling direction function in different planes, multiple motion gait planning methods of the snake-like robot are proposed. In order to evaluate the adaptability and maneuverability of the developed snake robot, extensive experiments were conducted in complex environments. The results demonstrate the robot's effectiveness in navigating through intricate settings, underscoring its potential for applications in various fields.

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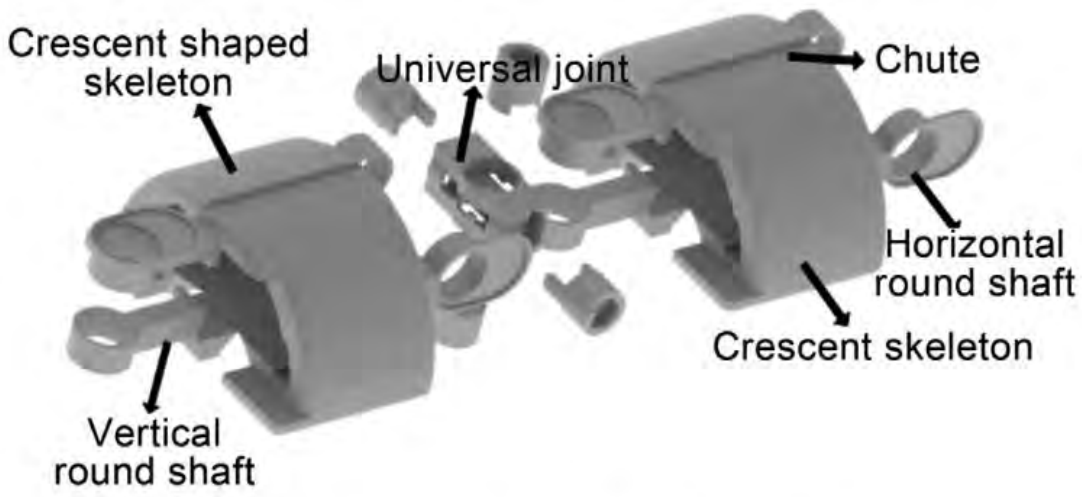

Fig. 1. Exploded view of rigid skeleton.

How NOKOV Contributes to the Research

During the experiments, markers were affixed to the snake robot, and an external vision system, NOKOV, was employed to record the data of motion.

Citation Xuanyi Zhou, Yuqiu Zhang, Zhiwei Qiu, Zhecheng Shan, Shibo Cai, Guanjun Bao, Locomotion control of a rigid-soft coupled snake robot in multiple environments, Biomimetic Intelligence and Robotics,Volume 4, Issue 2,2024,100148,ISSN 2667-3797,https://doi.org/10.1016/j.birob.2024.100148.

Link https://www.sciencedirect.com/science/article/pii/S2667379724000068

Mechanically Prestressed Pneumatically Driven Bistable Soft Actuators

Keywords

actuators and transmissions, grasping and fixturing, bistable mechanisms, soft robots

Abstract

Bistable soft robots are gaining momentum for their fast speed. This study presents a novel asymmetric mechanically prestressed, pneumatically driven, bistable laminated soft actuator. Its two orthogonal stable shapes are created by prestretching two orthogonal elastomer matrix composites before bonding them to a thin core layer. Two fluidic layers with fluid channels are bonded on either side of the core layer to actuate and trigger the snap-through process of the actuator. An analytical model is proposed as follows: the actuator net energy is calculated based on polynomials with unknown coefficients, and the stable shapes of the actuator are computed as a result of pneumatic pressure and external loads with the Rayleigh–Ritz method. Bistable actuators are fabricated with different prestrains, and motion capture and tensile loading experiments are conducted for model validation. A gripper is fabricated with two bistable actuators and demonstrated to grasp a variety of objects. Sensitivity studies are performed to identify the actuator response as a function of a variety of design parameters.

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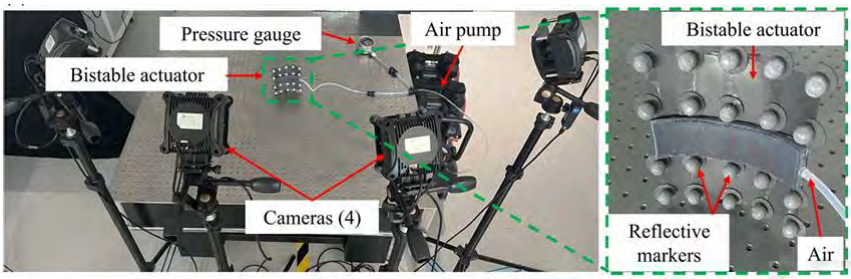

How NOKOV Contributes to the Research

In quasi static conditions, motion capture experiments are carried out to evaluate the shape of the actuator as it varies with pneumatic pres sure (Fig. 6(a)). The image of the actuator surface is acquired using a NOKOV motion capture system including four Mars2H cameras (resolution: 2.2 megapixels) and multiple reflective markers glued on the actuator surface.

Citation Zhou, Y., and Xu, Z. (July 20, 2023). "Mechanically Prestressed Pneumatically Driven Bistable Soft Actuators." ASME. J. Mechanisms Robotics. May 2024; 16(5): 051006. https://doi.org/10.1115/1.4062949

Link https://asmedigitalcollection.asme.org/mechanismsrobotics/article-abstract/16/5/051006/1164338/Mechanically-Prestressed-Pneumatically-Driven?redirectedFrom=fulltext

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Modeling the Soft Continuum Robot Based on Large Deflection Theorem

Keywords

Large deflection theory, soft robot, pneumatic muscle, modeling

Abstract

How to model the dynamics and represent the behavior of soft continuum robot accurately and efficiently has always been a challenging problem. In this paper, a new soft continuum robot dynamic model modeling idea is proposed, that is, the pneumatic soft continuum robot is regarded as a variable-stiffness beam structure when bending. The stiffness of the variable-stiffness beam structure is related to the input air pressure, and a large deflection theorem is employed for force analysis of the variable-stiffness beam. Finally, the soft continuous robot pressure model is used to solve the deflection curve equation. In the experiment, the bending posture of the soft continuum robot obtained by the visual capture system was compared with the simulation results, and the average error of the model was 8.5%

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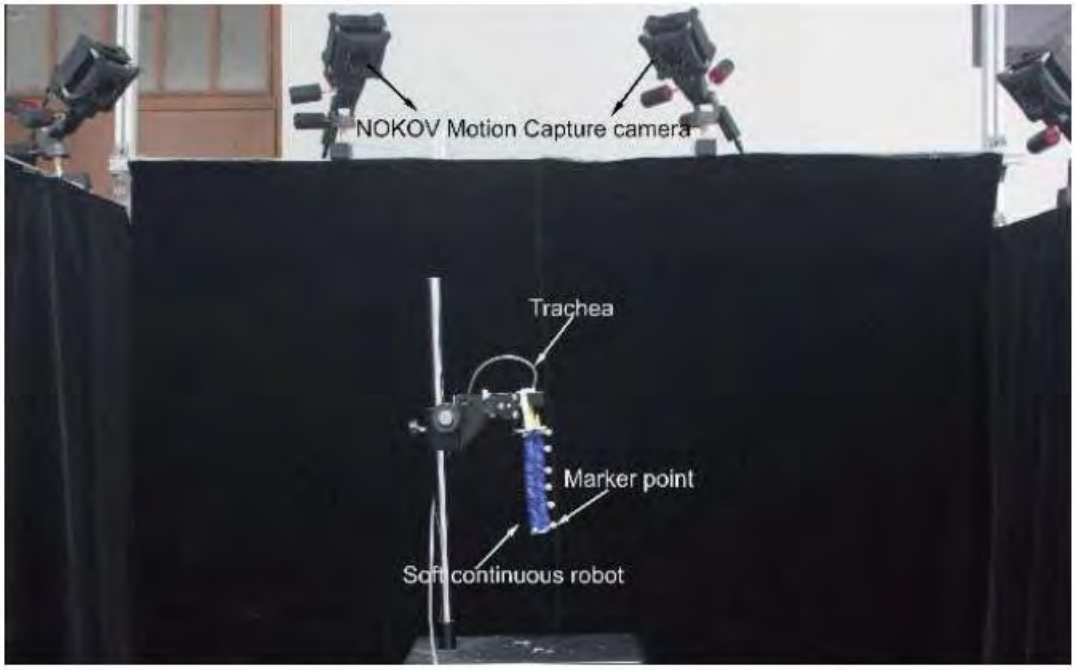

Fig. 5. Visual detection experiment platform

How NOKOV Contributes to the Research

Fig. 5 shows the soft continuum robot pneumatic platform and motion catching system. The kinematic model established in this paper describes the overall motion posture of the soft continuum robot at a given air pressure.Therefore, as shown in Fig. 5, the soft continuum robot is vertically installed on the fixture. The soft continuum robot is within the range of the visual capture system, and 6 reflective points (Marker point) are evenly attached on the side of the soft continuum robot. When the soft continuum robot is in its motion, the infrared camera (NOKOV Motion Capture System) can capture the relative position of the 6 points on the soft continuum robot in space, and later take out the 6 spatial positions and connect them with continuous smooth curves.

Citation Wang M, Wang W, Qiu Z, et al. Modeling the soft continuum robot based on large deflection theorem[C]//2021 IEEE International Conference on Robotics and Biomimetics (ROBIO). IEEE, 2021: 209-214.

Link https://ieeexplore.ieee.org/abstract/document/9739488

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Motion Analysis and Design on Pneumatic Actuators for Knee Assistive Devices

Keywords

FPBAs, Knee assistive devices, Wearable robotics, Soft robotics

Abstract

In recent years, more and more forms of soft bending actuators have emerged, which have been widely disseminated due to their advantages such as low cost and simple manufacturing, but their design and structural analysis remain blank. In this paper, human motion data acquisition and simulation experiments were carried out on a foldable pneumatic bending actuators to design a reasonable FPBAs structure. Firstly, the NOKOV experimental platform was used to collect human data for three groups of movements: walking, half squatting, and leg lifting. A total of four subjects participated in the experiment, and key information such as Angle and torque was obtained. Based on this experiment, combined with the simulation experiment, the number of airbags and the driving timing of the FPBAs device were analyzed, and the closed-loop expression of the torque provided by the airbags was derived.

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Fig.2 Optical three-dimensional motion capture experiment

How NOKOV Contributes to the Research

Abstract - In recent years, more and more forms of soft bending actuators have emerged, which have been widely disseminated due to their advantages such as low cost and simple manufacturing, but their design and structural analysis remain blank. In this paper, human motion data acquisition and simulation experiments were carried out on a foldable pneumatic bending actuators to design a reasonable FPBAs structure. Firstly, the NOKOV experimental platform was used to collect human data for three groups of movements: walking, half squatting, and leg lifting. A total of four subjects participated in the experiment, and key information such as Angle and torque was obtained. Based on this experiment, combined with the simulation experiment, the number of airbags and the driving timing of the FPBAs device were analyzed, and the closed-loop expression of the torque provided by the airbags was derived

Citation Sun J, Dai L, Yin Q, et al. Motion Analysis and Design on Pneumatic Actuators for Knee Assistive Devices[C]//2025 IEEE International Conference on Mechatronics and Automation (ICMA). IEEE, 2025: 1216-1221.

Link https://ieeexplore.ieee.org/document/11120820

Shape modeling and experimental validation of continuum robots

Keywords

Continuum robots, Kinematics, Static analyses, Shape modeling

Abstract

A mathematical model for the inverse kinematics and shape modeling of continuum robots is presented in this paper. This method simplifies the forward kinematics derivation process by introducing a rotation axis. In the inverse kinematics solution, an iterative approach is employed to try different initial values, and the optimal initial value is obtained by computing the condition number of the Jacobian matrix. Simulation experiments are verified that optimized initial values can effectively enhance the efficiency of inverse kinematics solution. Based on the Euler-Bernoulli beam theory, the shape modeling of continuum robots is derived, and the mathematical model of the relationship between robot shape and end loads is established. Finally, the mathematical model is verified through prototype experiments, demonstrating that the established shape modeling can achieve accurate simulation of deformation within a range where the bending angle is less than 90°, with errors within 10 %.

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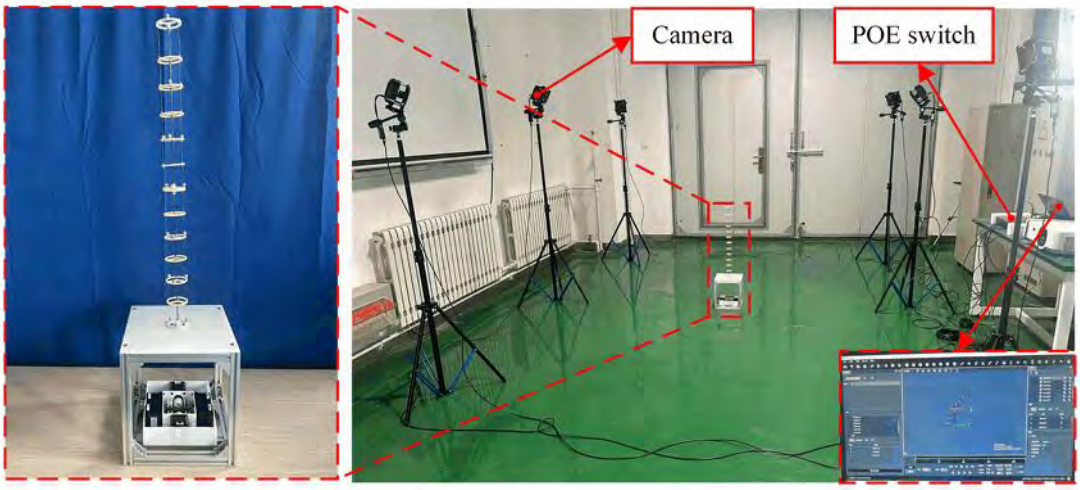

Fig. A1. The experimental platform.

How NOKOV Contributes to the Research

The experiment platform consists of a continuum robot prototype, a Nokov optical 3D motion capture system, and a drive unit, as shown in Fig. A1. To capture the shape of the continuum robot, reflective markers are attached to it. The Nokov optical 3D motion capture system uses motion capture cameras arranged in the space to precisely capture the 3D spatial positions of the reflective markers placed on the target.

Citation Tang S, Ji J, Yuan W, et al. Shape modeling and experimental validation of continuum robots[J]. Applied Mathematical Modelling, 2024, 135: 306-318.

Link https://www.sciencedirect.com/science/article/abs/pii/S0307904X24002993

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Shape Reconstruction of Extensible Continuum Manipulator Based on Soft Sensors

Keywords

extensible continuum manipulator, shape reconstruction, silicone rubber strain sensors

Abstract

Continuum manipulators can improve spatial adaptability and operational flexibility in constrained environments by endowing them with contraction and extension capabilities. There are currently desired requirements to quantify the shape of an extensible continuum manipulator for strengthening its obstacle avoidance capability and end-effector position accuracy. To address these issues, this study proposes a methodology of using silicone rubber strain sensors (SRSS) to estimate the shape of an extensible continuum manipulator. The way is to measure the strain at specific locations on the deformable body of the manipulator, and then reconstruct the shape by integrating the information from all sensors. The slender sensors are fabricated by a rolling process that transforms planar silicone rubber sensors into cylindrical structures. The proprioceptive model relationship between the strain of the sensor and the deformation of the manipulator is established with considering the phenomenon of torsion of the manipulator caused by compression. The physically extensible continuum manipulator equipped with three driving tendons and nine SRSS was designed. Comprehensive evaluations of various motion trajectories indicate that this method can accurately reconstruct the shape of the manipulator, especially under end-effector loads. The experimental results demonstrate that the mean (maximum) absolute position error of the endpoint is 1.61% (3.45%) of the manipulator length.

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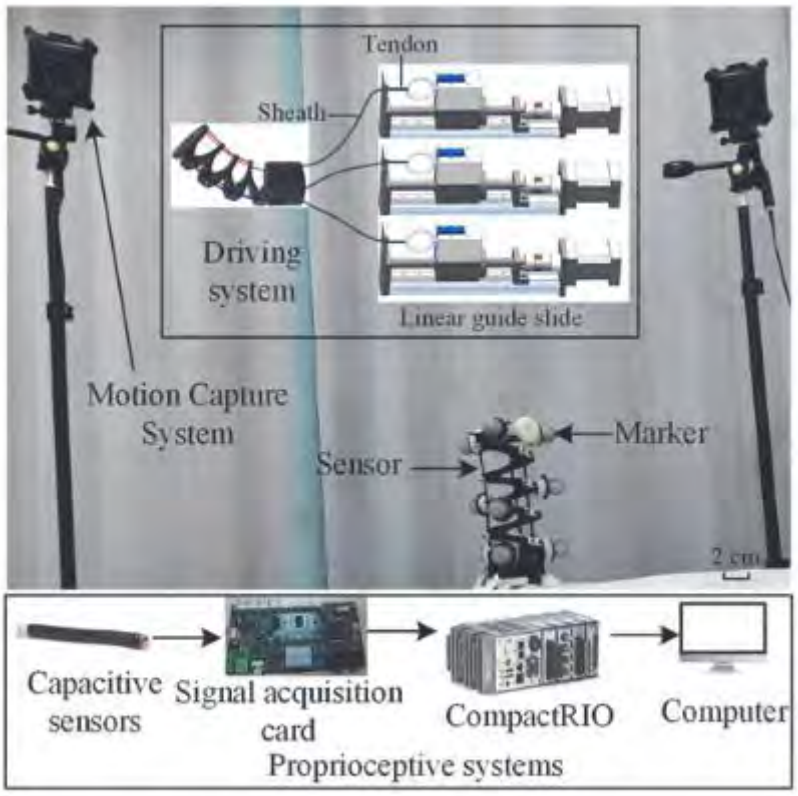

FIG. 6. An experimental setup for evaluating the accuracy of the body perception system.

How NOKOV Contributes to the Research

This actuation method is effective and avoids the need for force transmission structure design. The proprioceptive system mainly consists of nine stretchable cylindrical capacitive sensors, a signal acquisition card, and a national instruments real-time machine. A sensor, which spans three pitch lengths, is affixed to the manipulator at both ends, whereas its middle portion is allowed to slide freely within a constrained aperture.The true position of the markers installed on the manipulator is calculated using a motion capture system (developed by Beijing NOKOV Science & Technology Co., Ltd., equipped with eight Mars 2H lenses distributed around the manipulator).

Citation Wang P, Feng Y, Zheng Z, et al. Shape Reconstruction of Extensible Continuum Manipulator Based on Soft Sensors[J]. Soft Robotics, 2024, 11(6): 994-1007.

Link https://www.liebertpub.com/doi/abs/10.1089/soro.2023.0094

Soft Pneumatic Helical Actuators With Programmable Variable Curvatures

Keywords

Analytical modeling; Helical actuators; Pneumatic actuators; Soft gripper; Soft robotics

Abstract

This letter proposes novel variable-curvature soft helical actuators (VC-SHAs) using fluidic prestressed composites (FPCs) for enhanced grasping performance. A third-order three-dimensional chained composite model called 3D-CCM is developed to pre-program variable curvatures of SHAs and predict their actuation responses. The proposed actuator design increases shape-matching areas between the objects and the soft actuators, highly improving grasping performance. Various VC-SHAs are fabricated and tested to validate the model and parametric studies are conducted to identify the effects of key parameters on actuator responses. A bioinspired passive dynamic gripper is developed with three VC-SHAs. Loading tests are conducted to evaluate its grasping success rates and maximum payload for various objects and object sizes, achieving a maximum payload of 26.56 N. The gripper is integrated to a drone to demonstrate its capability to perch on pipelines of different sizes and angles, and various objects.

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How NOKOV Contributes to the Research

Motion capture tests are performed to evaluate the accuracy of the 3D-CCM. In quasi-static conditions, experiments are carried out to reconstruct the actuator's helical shape, which varies with pneumatic pressure. The centerline of the midplane for the actuator is acquired using a NOKOV motion capture system including eight Mars2H cameras.

Citation Z. Xu, J. Liang and Y. Zhou, "Soft Pneumatic Helical Actuators With Programmable Variable Curvatures," in IEEE Robotics and Automation Letters, vol. 9, no. 7, pp. 6632-6639, July 2024, doi: 10.1109/LRA.2024.3410165.

Link https://ieeexplore.ieee.org/document/10549798

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Stiffness modulation in a 3-DoF pneumatic soft actuator for single-port transvesical prostatectomies

Keywords

urgical robotics ,soft actuators, multi-DoF, stiffness modulation, transvesical prostatectomy

Abstract

Soft actuators have demonstrated potential in minimally invasive surgery (MIS), requiring multiple degrees of freedom and stiffness modulation facilitated by pneumatic antagonistic chambers. However, the hollow central passage in these actuators for single-port surgery complicates the internal stress distribution during the inflation of multiple chambers, making stiffness modulation mechanisms difficult to understand. In this study, a finite element analysis model is developed to explore the combined effect of the internal stress distribution and duct structure on the stiffness modulation in soft actuators equipped with multiple pneumatic antagonistic chambers. A prototype is developed to cross-validate the simulation and examine the effects of various antagonistic chambers on the stiffness modulation. The findings confirm that inflating specific chambers alters the internal stress distribution of the actuator by creating bending moments that influence deformation responses to external loads. These moments impact the stiffness and structure of the hollow central duct by modifying its geometrical moment of inertia and affecting the lengths of the tensile and compressive regions during bending, further influencing the stiffness. The effects of bending moments and the geometrical moment of inertia on stiffness modulation vary across different actuator sections owing to the varying lengths of the tensile and compressive regions during bending. These stiffness modulations affect the tip bending, force, and response time. The study findings provide insights into the mechanism of stiffness modulation for the design of soft actuators for complex MIS.

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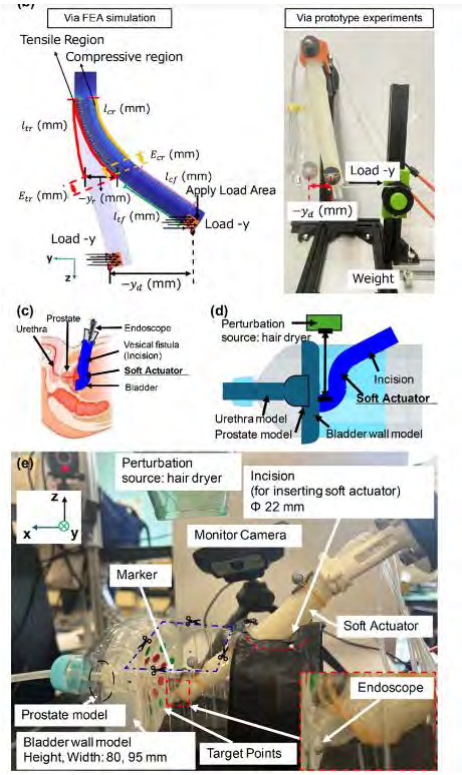

How NOKOV Contributes to the Research

A rope was securely fastenedat one end to the top of the soft actuator and at the otherend to a weight through a pulley system, thereby imparting astable load in the negativey-direction. A motion-capture system (Mars 1.3 HW, Beijing NOKOV Science & Technology Co., Ltd, CN) was utilized to accurately measure the deflec-tion of the actuator under these applied loads. Markers wereplaced on the actuator, enabling precise tracking and meas-urement of movements and deformations.

Citation Lu Y, Zhou Z, Igarashi T, et al. Stiffness modulation in a 3-DoF pneumatic soft actuator for single-port transvesical prostatectomies[J]. Smart Materials and Structures, 2024, 34(1): 015021.

Link https://iopscience.iop.org/article/10.1088/1361-665X/ad9973

Temperature Driven Multi-Modal/Single-Actuated Soft Finger

Keywords

Soft robotic actuator, Humofit, Variable stiffness, Fiber-reinforced soft actuator, Multiple motion modes

Abstract

Soft pneumatic fingers are of great research interest. However, their significant potential is limited as most of them can generate only one motion, mostly bending. The conventional design of soft fingers doesn't allow them to switch to another motion mode. In this paper, we developed a novel multimodal and single-actuated soft finger where its motion mode is switched by changing the finger ' s temperature. Our soft finger is capable of switching between three distinctive motion modes: bending, twisting, and extension-in approximately five seconds. We carried out a detailed experimental study of the soft finger and evaluated its repeatability and range of motion. It exhibited repeatability of around one millimeter and a fifty percent larger range of motion than a standard bending actuator. We developed an analytical model for a fiber-reinforced soft actuator for twisting motion. This helped us relate the input pressure to the output twist radius of the twisting motion. This model was validated by experimental verification. Further, a soft robotic gripper with multiple grasp modes was developed using three actuators. This gripper can adapt to and grasp objects of a large range of size, shape, and stiffness. We showcased its grasping capabilities by successfully grasping a small berry, a large roll, and a delicate tofu cube.

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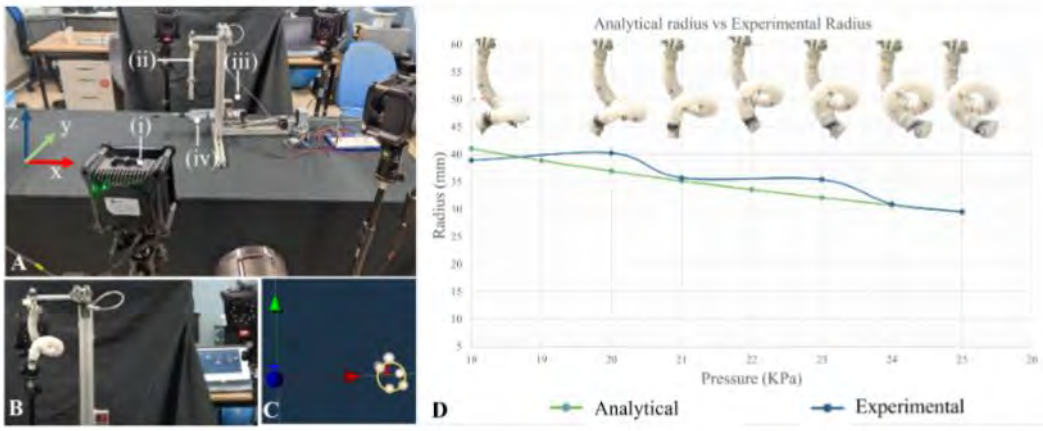

Figure 7: Setup and output for the verification of the developed analytical model(A) Motion capture cameras surrounding the actuator setup. (i)Motion capture camera. (ii) Soft actuator. (iii) Pressure sensor. (iv)Air pressure input. (B) Twisting motion with markers on. (C) Fitted circle over markers captured by the mocap system. (D) Analytical radius vs Experimental radius.

How NOKOV Contributes to the Research

4.2.Experimental Verifcation
The developed analytical model was verified experimentally. The experimental setup can be seen in Fig. 7A. Seven markers of 3mm diameter were placed along the edge of the soft actuator (Fig. 7B). We chose 3mm markers to ensure little to no change in the actuator's motion due to the marker's weight. Smaller markers were tried as well, but the motion capture system failed to detect them in most cases. As for the rest of the setup, six Nokov motion capture cameras were arranged around the actuator. The distance of each camera was set manually to obtain the best output possible. The actuator was actuated with the same pressure input using a ball screw-driven air piston. The Humoftl was stimulated by pouring hot water over the actuator with a small syringe. This hot stimulation softens the humoft and allows the actuator to execute twisting motion for approximately over a minute. A pressure sensor was used to observe the pressure in the actuator throughout its motion. The actuator was actuated ten times by air pressure input at a slow speed. The markers were observed from the top view, and a circle fitting method was implemented on them. This was to obtain the radius of the circle which all the markers pass through, i.e., the radius of the twist.

Citation Kumar, Prashant, Weiwei Wan, and Kensuke Harada. "Temperature driven multi-modal/single-actuated soft finger." Robotics and Autonomous Systems (2026): 105374.

Link https://www-sciencedirect-com-443.webvpn.hdu.edu.cn/science/article/pii/S0921889026000473

Twist-Induced bifurcation and path manipulation in compressed ribbons

Keywords

Elastic ribbon, Multi-stability, Bifurcation reconstruction, Snap-through, Path manipulation

Abstract

In this paper, we investigate the nonlinear behaviour of ribbons subjected to coaxial compression and twisting through theoretical, numerical, and experimental approaches. Using anisotropic Kirchhoff rod theory and continuation techniques, we construct global bifurcation diagrams and identify stability transition points via the conjugate-point test. Here, we show that the twist induces supercritical pitchfork bifurcations in ribbons, giving rise to a rich landscape of multi-stability with up to four coexisting stable states. With increasing twist, we observe stability transitions between the fundamental and second Euler buckling modes. Moreover, gravity triggers a global bifurcation reconstruction characterized by the emergence of saddle-node bifurcations. These gravity-induced transformations allow for multiple, controllable snap-through pathways between stable states. We extend a mixed-curvature-based numerical optimization method to predict snap-through destinations and propose a general path-planning framework to navigate between stable configurations. Experiments on ribbons with varied aspect ratios corroborate the theoretical predictions and demonstrate the viability of programmable transitions in multi-stable systems. Our findings provide new insights into bifurcation and snap-through behaviour in slender structures, with potential applications in mechanical metamaterials, flexible electronics, and soft robotics.

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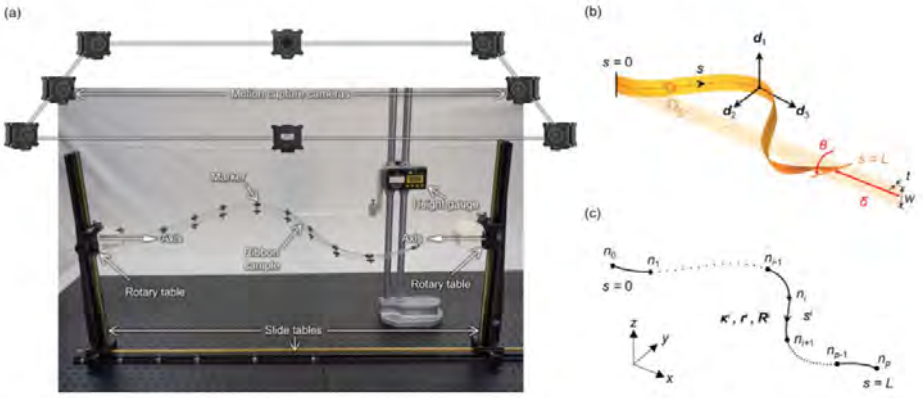

Fig. 1. Problem setup for theoretical, numerical, and experimental analysis. (a) Experimental setup. Both ends of a naturally straight ribbon are clamped onto rotary tables, and they are aligned along the vertical direction using two oppositely oriented slide tables. The horizontal slide table induces the end-shortening deformation. The height gauge measures the height of any specific point along the ribbon, and the markers on edges of the ribbon, together with motion capture devices, track the buckling mode during deformation. (b) Geometry of the ribbon in the reference configuration Ω_0 and the current configuration Ω. The ribbon has a total length L (x-direction), width w (z-direction), and thickness t (y-direction). It is subjected to coaxial compression and twisting boundary conditions, with δ representing the end-shortening and θ representing the end-twisting. An orthonormal director frame is defined along the ribbon's centerline at the local coordinate s, with d_1 in the width direction, d_2 in the thickness direction, and d_3 in the tangent direction. (c) Discrete schematic representation of the ribbon. The total length L is divided into p elements, resulting in $p+1$ nodes, labelled from n_0 to n_p. Quantities κ^i, r^i and R^i are defined along the element between nodes n_i and n_{i+1}.

How NOKOV Contributes to the Research

To apply end-twisting θ (±0.1°), both ends of the ribbon are clamped onto rotary tables (KSK, China), which are mounted on vertical slide tables (KSK, China) to ensure alignment of the rotational axes. These vertical slide tables are in turn fixed to a horizontal slide table (KSK, China), allowing for the application of end-shortening δ (±0.1 mm). The height of any point along the ribbon can be measured with a height gauge (Hongfeng, China). Markers are affixed to the edges of the ribbon in the width direction, spaced at intervals of 100 ± 0.5 mm along the length, to track the ribbon's deformation. A motion capture system (NOKOV, China) consisting of eight NOKOV motion capture cameras and a computer monitors the marker positions throughout the deformation process, providing detailed data on the buckling modes.

Citation Feng T, Chen J, Wong J W, et al. Twist-induced bifurcation and path manipulation in compressed ribbons[J]. Journal of the Mechanics and Physics of Solids, 2025: 106328.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001582920300002

Versatile Rigid-Flexible Coupling Modules: Enhancing Soft Origami Structures with Cable-Driven Parallel Mechanisms

Abstract

Soft robots have garnered significant attention due to their adeptness in addressing challenges that traditional rigid robots struggle to effectively manage, including adaptability to unstructured environments and safe human–robot interactions. However, these modular soft robots always show limitations in coping with application requirements due to the defects of their building blocks, including limited motion patterns, poor repetitive positioning accuracy, and weak load-bearing capacity. Herein, a rigid parallel structure on the exterior of a soft origami structure is introduced, developing a rigid-flexible coupling building block. In this combined theoretical and experimental study, the geometric parameters to realize the coupling synergy between the two structures in terms of kinematics are adapted. Then, diverse experiments are conducted to characterize the performance of this building block, indicating that this building block not only has all basic motion patterns (i.e., contraction ΔH_{max} = 30.78 mm, bending θ_{max} = 59.96°, and twisting φ_{max} = 33.67°) but also exhibits high repeatable positioning accuracy and strong load-bearing capacity. Based on this building block, a soft continuum robot that showcases its versatility, such as flexibly twisting light bulbs and using bending motion pattern to grasp items of varying weights is developed.

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How NOKOV Contributes to the Research

Here, all quantifiedresults of motion are measured using an optical motioncapture system (Mars 12H, NOKOV, China). Then, we quan-tified the deformation limits of building blocks in differentmotion patterns, as shown in Figure 5B. For example, thelimits of this building block in contraction deformationreaches ΔHmax = 30.78 mm; therefore, the height of this building block can be reduced to 73.91% of its initial height. Itis worth noting that twisting motion is well isolated when thismodule undergoes contraction deformation. Therefore, weconsidered that decoupling is achieved between these motionpatterns of this building block. In addition, we also measuredthe maximum angles of this building block in bending andtwisting deformation, as 59.96° and 33.67°, respectively.

Citation Wang J, Yang H, Zhang J, et al. Versatile rigid-flexible coupling modules: enhancing soft origami structures with cable-driven parallel mechanisms[J]. Advanced Intelligent Systems, 2025: 2401008.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001556296700034

Visual control of a cable-driven flexible robotic arm with a spinal structure based on video understanding

Keywords

Large language model, Vision servo control, Flexible robotic arm, Deep learning

Abstract

Flexible robotic arms have higher degrees of freedom, making them increasingly popular in tasks such as grasping in narrow environments. However, their high-compliance characteristics and occlusion in the environment pose considerable challenges in the precise control consistent with human requirements. This study combines vision-based knowledge representation with a large language model to help a cable-driven flexible robotic arm with a spinal structure better understand human intentions and mimic human actions. In particular, a visual servo system closely coupled with the flexible robotic arm is designed, which can effectively reduce the impact of occlusion on visual positioning. In a narrow experimental environment, the recognition accuracy of the coupled visual dynamic adjustment system improved by 34.8% compared with relying solely on visual recognition from the end of the arm, and by 28.7% compared with using the external camera visual recognition alone. Subsequently, aimed to perform fine manipulations of the flexible robotic arm, a data driven nonlinear modeling method is proposed and a coarse-to-fine visual grasping control system is designed. Experiments across eight task scenarios validate the precise control and interactivity of the system in narrow environments using a flexible robotic arm with a spinal structure.

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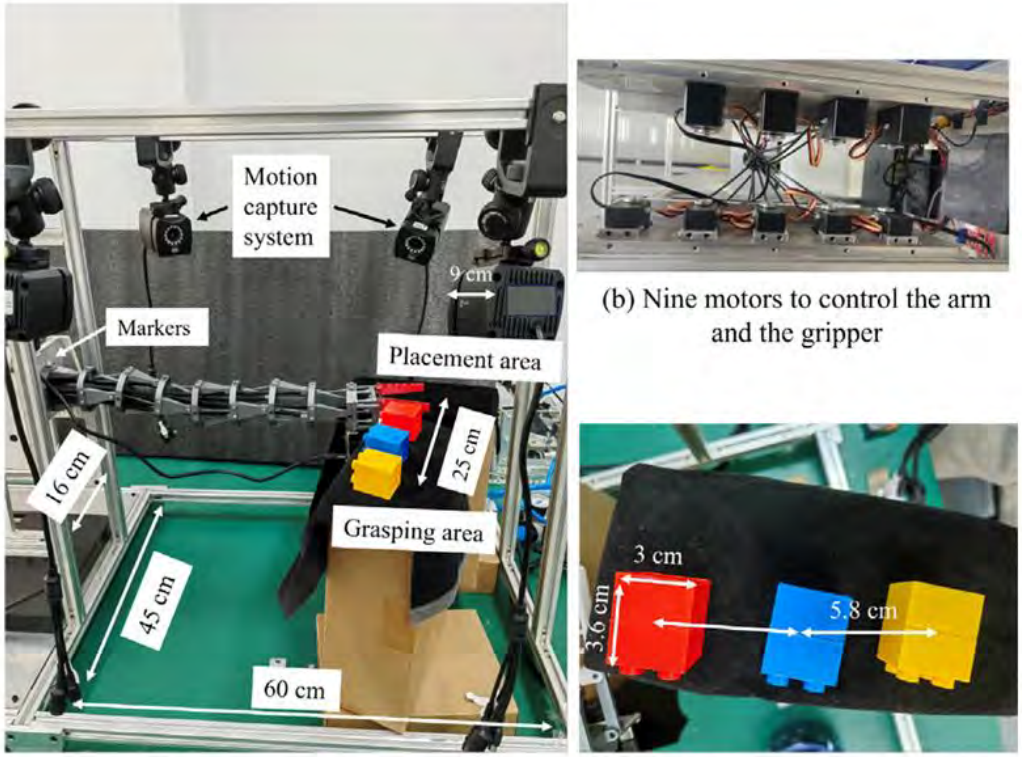

(a) Experimental environment

(b) Nine motors to control the arm and the gripper

(c) The distance between blocks

Fig. 7. Experimental environment description.

How NOKOV Contributes to the Research

In this section, to perform data collection and cleaning process, a motion capture system named Pluto 1.3C from BEIJING NOKOV SCIENCE & TECHNOLOGY was used to capture the coordinates of the target points in space. The accuracy of the motion capture system was ±0.5 mm. Coordinate capture balls were placed on the wrist and base of the flexible robotic arm to capture the end effector coordinates of the flexible robotic arm at different positions. Additionally, three non-collinear capture balls were placed in the space to facilitate transformations between coordinate systems.

Citation Zhang X, Wu X, Fu K, et al. Visual control of a cable-driven flexible robotic arm with a spinal structure based on video understanding[J]. Control Engineering Practice, 2025, 160: 106303.

Link https://www.sciencedirect.com/science/article/abs/pii/S0967066125000668

Multimodal Quad-Finger Soft Robotic Hand With Dual-Chamber Origami Actuator for Large-Workspace Manipulation

Keywords

large workspace; multimodal manipulation; origami actuator; soft robotics hand

Abstract

Increasing demands for multimodal manipulation and large-workspace operation in complex environments are driving interest in compliant, safe, morphologically adaptable soft robotic hands for humanoid robotics. This article presents a multimodal quad-finger soft robotic hand, termed the QDO hand, in which each finger is actuated by a dual-chamber straight-curved origami prismatic (SCOP) actuator. By regulating positive and negative pressures in the dual chambers, each finger achieves multiple motion modalities with a large range of motion, including axial extension-contraction and bidirectional bending. Based on these capabilities, a Dual-Chamber-Induced Finger-Level Multimodal Gesture (DCI-FLMG) scheme is proposed to coordinate modalities across fingers and generate diverse hand-level gestures, including anthropomorphic in-hand gestures (AIHGs), dorsal bending gestures (DBGs), and axial extension-contraction gestures (AECGs). A kinematic model of the QDO hand is established and compared with a constrained human grasping motion (CHGM) hand that excludes finger abduction-adduction. Results show that the QDO hand achieves a total workspace approximately 5.2 times that of the CHGM hand while covering about 70% of its reachable area. Demonstrations validate AIHGs, DBGs, and AECGs in representative scenarios involving manipulation, posture transitions, and human-robot collaboration, highlighting their potential for dexterous manipulation in complex, unstructured, narrow-space environments.

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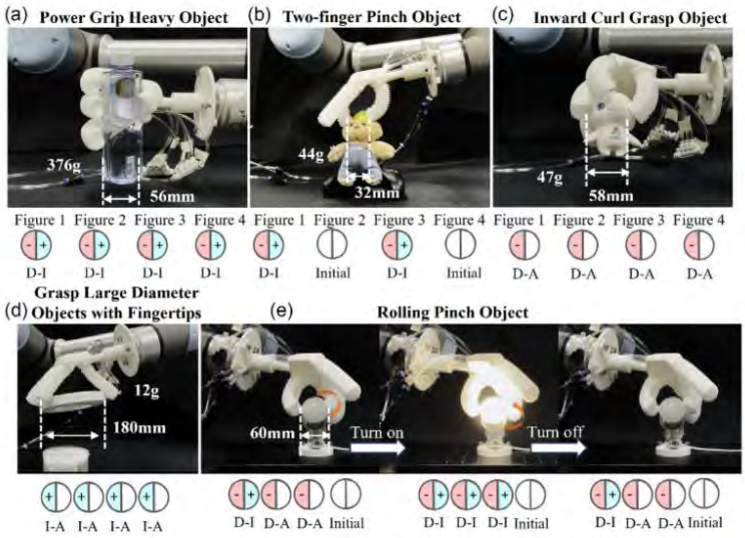

FIGURE 6 | Demonstration of in-hand manipulation. (a) Power grasp of a 376 g cylindrical bottle (56 mm diameter). (b) Two-finger piching a 44 g toy figure (32 mm width). (c) Inward curl grasping a 47 g (58 mm diameter) object. (d) Grasping laege diameter (180 mm) object with fingertios. (e) Functional interaction with a rotary switch (60 mm diameter), where the QDO Hand performs continuous in-hand rotation to turn the light on and off.

How NOKOV Contributes to the Research

To evaluate whether the motion trajectories of the SCOP soft finger and QDO hand under various operation modes accurately cover their theoretical workspace, and to further assess the accuracy and practical feasibility of their motion capabilities, a 3D motion capture system (Infrared Camera, NOKOV) was established, as shown in Figure 5a. Reflective markers were attached to the fingertips, allowing real-time recording of the end-effector trajectories of the QDO Hand under different operation modes. These trajectories were then mapped into a theoretical 3D workspace for comparative analysis.

Citation Tan Q, Zhou S, Chen Y, et al. Multimodal Quad-Finger Soft Robotic Hand With Dual-Chamber Origami Actuator for Large - Workspace Manipulation[J]. Advanced Intelligent Systems, 2026: e70388.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001742954000001

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Efficient path planning for continuum robotic arm using improved RRT algorithm

Keywords

Continuum robotic arm; Kinematic analysis; Path planning; Curve fitting

Abstract

Continuum robotic arms require path planning in narrow, obstacle-rich environments. Existing methods primarily use sampling-based algorithms like rapidly-exploring random tree (RRT), which suffer from strong randomness, slow convergence, and suboptimal results. To address these issues, this study proposes an improved RRT algorithm. First, the initial step size is calculated using environmental information, with obstacle data dynamically adjusting the step size during expansion to enhance exploration. Second, target-biased sampling combined with an optimized nearest-node selection strategy improves search efficiency for rapid feasible path generation. Finally, high-order B & eacute;zier curves were applied to optimize the path for smoothness. MATLAB simulations and physical experiments demonstrate the algorithm efficiently generates valid paths among multiple obstacles in 3D space. Compared to conventional RRT, it reduces path cost by 33.1 %, planning time by 98.1 %, and node count by 72.1 %, validating its effectiveness.

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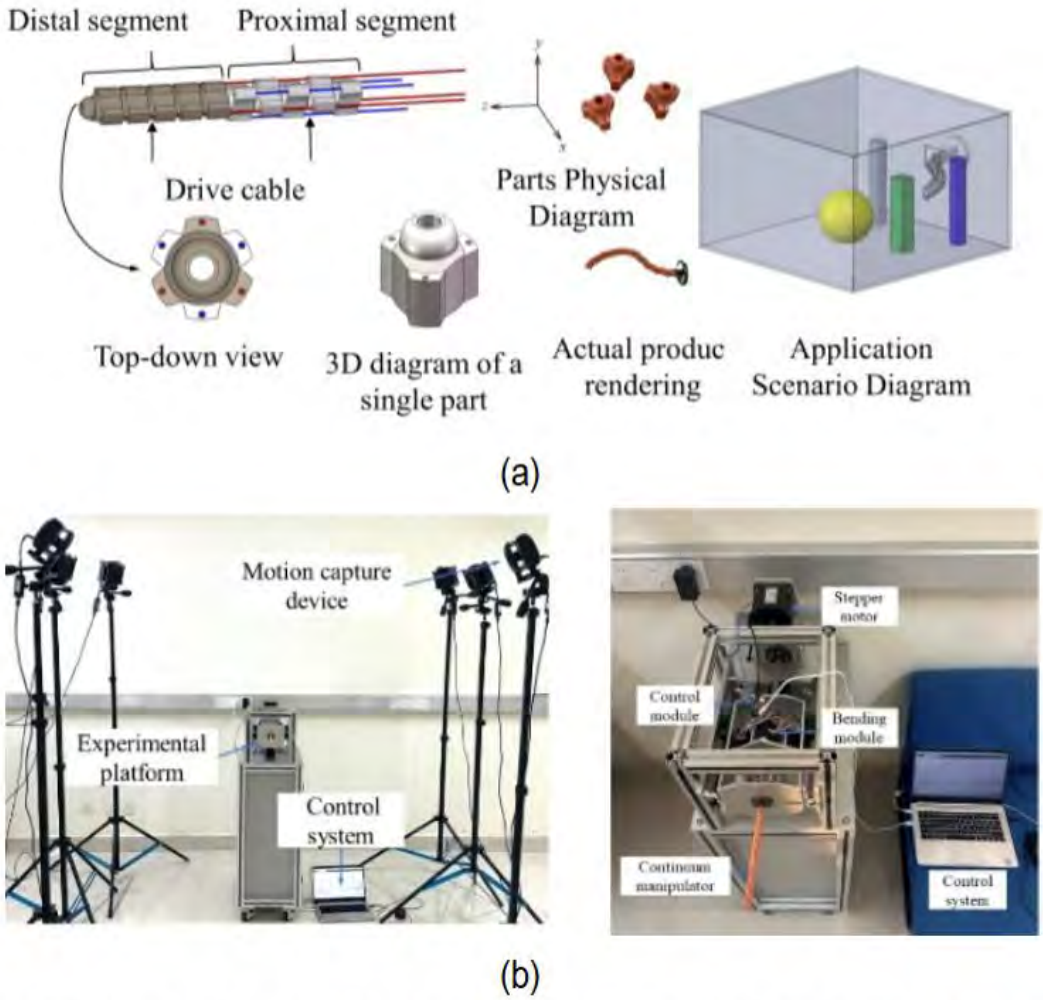

Fig. 15. Application scenarios and experimental platform: (a) diagram and application scenarios; (b) setup of the experimental platform.

How NOKOV Contributes to the Research

The NOKOV motion capture system was used to collect 3D point coordinates for analysis, as shown in Fig. 17(a) presents a comparison between the theoretical simulation path and the experimental path, where Fig.17(b) displays the error analysis.

Citation Gao Y, Tang X, Chen Y, et al. Efficient path planning for continuum robotic arm using improved RRT algorithm[J]. Journal of Mechanical Science and Technology, 2026: 1-13.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001762617600001

A Portable Soft Robotic Glove with Fully Functional Thumb Assistance for Complex Dexterous Fine Motor Skills

Keywords

assist as needorigami actuatorrehabilitationsoft robotic glovethumb

Abstract

Stroke causes millions of cases of hand disability annually, impairing fine motor skills needed for daily tasks like pinching, circumduction, phone swiping, cap twisting, and thumb opposition. Existing hand exoskeletons and soft gloves often lack adequate thumb support, are bulky, and rely on unsensorized open-loop control. We developed a portable soft robotic glove that provides comprehensive, task-oriented assistance for the thumb and fingers. A novel soft continuous-segmented dual-chamber origami thumb actuator enables active carpometacarpal abduction/adduction, flexion/extension, metacarpophalangeal flexion/extension, and interphalangeal extension, covering the full functional range and generating 18 N tip force-about twice what's required to overcome typical post-stroke spasticity. The glove integrates a sensorized portable driving and an \"assist-as-needed\"controller to minimize support and maximize user engagement. Three chronic stroke participants with varied impairment levels performed pinching, lateral pinching, circumduction, phone swiping, cap twisting, and thumb opposition while wearing the glove; all completed the tasks. Across participants, the glove increased lateral pinch force by 62.9% and expanded thumb range of motion ninefold. These results indicate the system's potential as a practical solution for dexterous, task-oriented rehabilitation to restore functional hand movements and improve daily living.

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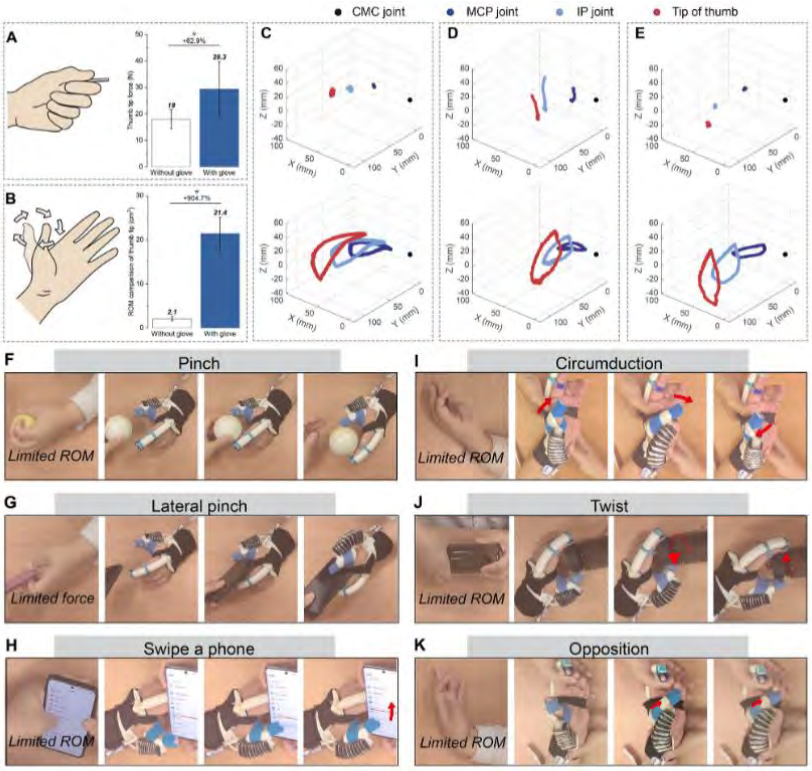

FIGURE 4 | Subject test results. (a) Wearing the glove increases lateral pinch force by 62.9% compared to not wearing the glove. (b) Wearing the glove increases the range of motion for thumb circumduction by 904.7%. Range of motion comparisons for subjects S1 (c), S2 (d), and S3 (e) between wearing the glove and not wearing it. (f) Photos of test activities: pinch (f), lateral pinch (g), swiping a phone (h), circumduction (i), twisting a cap (j), and opposition (k) on subjects.

How NOKOV Contributes to the Research

To demonstrate the potential range of motion of the dual-chamber actuator, a model hand is constructed with a universal joint at the CMC joint position to represent this joint. The dual-chamber actuator is applied at the same position when wearing, as shown in Figure 2h. Two tests are conducted: first is the circumferential rotation test as illustrated in Figure 2i. To quantitatively evaluate the workspace of the proposed mechanism, 3D spatial coordinates of the mechanism's end effector are captured in real time using the NOKOV motion capture system. A healthy male subject with 180 cm height is recruited, conducting the circumferential movement to compare the range data with that of the model hand directly. The range shown in Figure 2i is similar to that of a database from 28 subjects [55]. Analysis reveals that the mechanism achieves 86.8% coverage of the natural thumb motion range, as shown in Figure 2i covering the requirements of ADL, indicating its feasibility in terms of motion range.

Citation Xie D, Wang Z, Ye Z, et al. A Portable Soft Robotic Glove with Fully Functional Thumb Assistance for Complex Dexterous Fine Motor Skills[J]. Advanced Science, 2026: e76275.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001804393600001

基于 GABP 神经网络的双段柔性机器人末端位置控制研究

关键词

GABP 算法;柔性机器人;运动控制模型;

摘要

绳驱式脊柱状连续体机构实际弯曲形态与标准圆弧形状存在偏差，建立精确的运动控制模型困难。针对双段式六软轴驱动的蛇形仿生柔性机器人结构，通过融合遗传算法与反向传播神经网络 GABP，研究双段式柔性机器人末端位置精确控制问题。通过 SolidWorks 和 ADAMS 联合仿真，建立柔性机器人末端的 X、Y、Z 坐标和 6 根软轴的拉伸长度的映射数据库，利用数据库分别训练了标准反向传播 BP 神经网络和 GABP 神经网络模型，并且优化模型参数。最后设计机器人末端运动轨迹，使用 BP 和 GABP 神经网络模型分别通过 ADAMS 仿真平台和模型机上验证柔性机器人末端位置精度。结果表明：标准 BP 和 GABP 模型都可以实现柔性机器人末端的位置控制，融合了遗传算法的神经网络模型（最大误差：εx=0.73 mm，εy=0.78 mm，εz=1.96 mm）相对于标准 BP 神经网络模型（最大误差：εx=3.13 mm，εy=1.78 mm，εz=1.96 mm）在控制柔性机器人末端运动的位置精度得到了显著提升。

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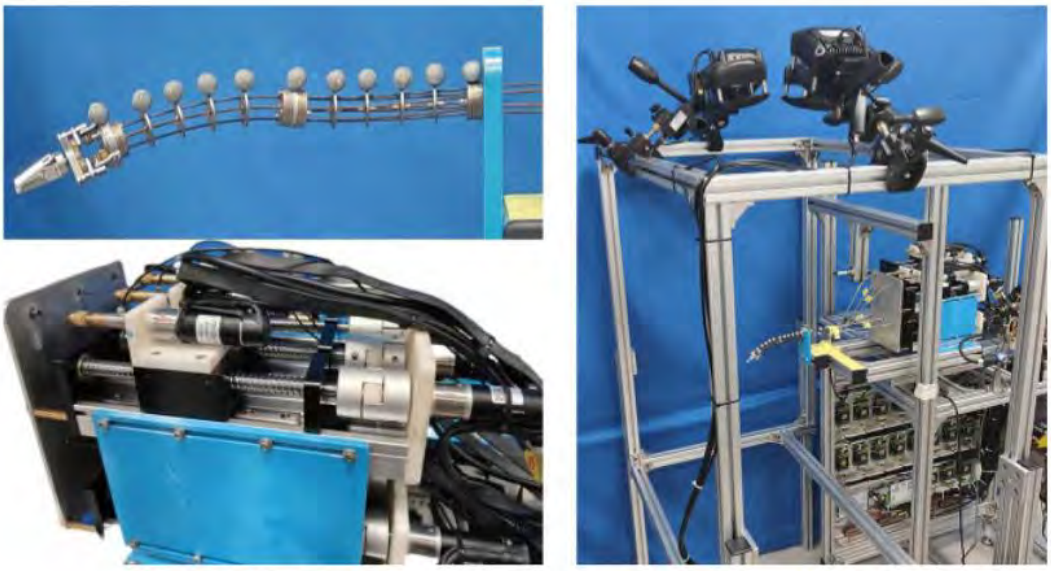

（a）连续体机器人　　（b）动作捕捉系统

图 10　连续体机器人与 NOKOV 动作捕捉系统集成展示

NOKOV 度量动作捕捉在研究中的应用摘录

4 运动轨迹预测验证
本研究采用泰科智能 CBL2040 型号的直流伺服电机作为动力源，通过其转动带动直线导轨。直线导轨上的滑块通过连接件与软轴相连，实现了电机转动到软轴直线位移的转换，从而达成连续体机械臂位姿的改变，与此同时利用 NOKOV 动作捕捉系统记录机械末端坐标:如图 10 所示。本系统采用闭环位置控制策略，通过编码器反馈滑块的实时位置，与目标位置进行比较，调整电机的驱动信号，以确保软轴位移的精确控制，实验中通过多次测试，验证了软轴位移的一致性和精度，证实了控制策略的有效性。

引用格式 张治,刘铨权,董佳祥,等.基于 GABP 神经网络的双段柔性机器人末端位置控制研究[J].机电工程技术,2025,54(13):142-148.

链接

https://kns.cnki.net/kcms2/article/abstract?v=yqBhao7Q9gwf-bUK9WXY3WhN5W2r1aaDFAqHjLegc11QKMtEyQFkznY2NflEZiAsbaYRgJ4Kegp-DxL7iKWmlJnTu8_wCcEK7qtxZoihGlsutK1tc4YgJ01Yi6OMH-IE0NmNysRwqTt_IV4DxXPyJEJANMWJum0lfhX_jdDmxw3jNzDyoGpycA==&uniplatform=NZKPT&langua

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基于逆运动学的柔性机械臂末端定位控制

关键词

线驱动柔性机械臂；逆运动学；末端定位；CoppeliaSim

摘要

针对具有形变特性的柔性机械臂，在运动过程中存在末端不易定位控制或定位精度低的问题，设计了一种线驱动柔性机械臂样机，通过分析其运动机理推导末端位置空间、臂体形态空间以及驱动空间三者之间的逆运动学关系；然后，提出了基于逆运动学模型的柔性机械臂末端定位控制方案；最后，利用 CoppeliaSim 仿真平台建立了柔性机械臂仿真模型，并在该仿真平台中应用逆运动学关系进行柔性机械臂运动控制过程中末端定位仿真分析，仿真结果验证了所建立逆运动学模型的有效性及基于该模型的柔性机械臂末端定位控制方法的合理性。

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图 11　柔性机械臂实物样机及试验平台

NOKOV 度量动作捕捉在研究中的应用摘录

试验平台主要包含柔性机械臂、NOKOV 动作捕捉系统、反光标记球及用于固定的铝合金框架。其中动作捕捉系统主要用于记录柔性机械臂运动过程中末端位置变化数据。

引用格式 马丛俊,赵涛,向国菲等.基于逆运动学的柔性机械臂末端定位控制[J].机械工程学报,2021,57(13):163-171.

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基于软轴拉扭协同驱动的连续体机器人机构设计与控制系统研究

关键词

连续体机器人;软轴拉扭驱动;神经网络控制;无模型控制;Adams 仿真;

摘要

随着微创手术技术的快速发展,连续体机器人因其高灵活性和适应性,在咽喉手术等狭小空间操作中展现出巨大的应用潜力。然而,传统刚性机器人难以满足复杂手术环境下的高精度和高顺应性需求,而完全柔性机器人又存在刚度不足的问题。针对这一问题,本文以咽喉手术为应用背景,提出了一种软轴拉扭协同驱动的连续体机器人系统,旨在实现高精度、高灵活性的手术操作。本文的主要研究内容及成果如下: 首先,基于咽喉手术的空间限制和操作需求,设计了连续体机器人的机械结构。柔性段采用超弹性材料,刚性段通过齿轮组传动机构实现高精度运动。通过结构优化,机器人具备了更好的适应性和灵活性,能够满足口腔内狭小空间的手术需求。 随后,在 Adams 仿真平台对优化后的连续体机器人模型进行动力学建模,并采集大量仿真实验数据。利用处理后的数据建立了神经网络的训练数据库,为后续的无模型控制策略提供了数据支持。 进一步,采用 BP 神经网络模型代替传统的物理模型,建立了机器人末端位置与输入之间的映射关系。通过神经网络的非线性拟合能力,实现了对机器人末端位置的高精度控制,避免了传统运动学模型中的简化假设和人为误差。 最后,完成了机器人硬件平台、控制系统和软件交互系统的搭建。通过 Adams 与 Matlab/Simulink 的联合仿真,验证了机器人系统的动态响应特性。最后,在仿真平台上进行了 L 形、O 形和 S 形轨迹跟踪实验,以及在实体机上与仿真平台上同时进行机械臂 S 形姿态对比实验。实验验证了轨迹跟踪的准确性、动力学仿真模型的有效性以及本文所提出控制策略在实际应用中的可行性和有效性。 实验结果表明,基于神经网络的控制器能够有效实现机器人末端的精确控制。本文的研究成果为连续体机器人在微创手术中的应用提供了新的解决方案,具有重要的理论意义和临床应用价值。

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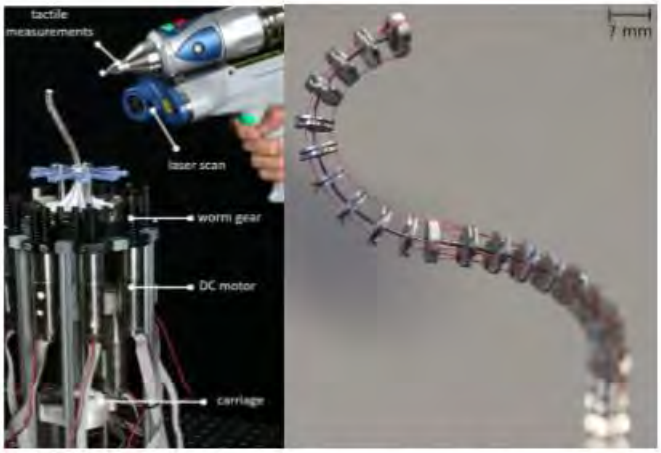

图 1-1 一种具有可延伸截面的肌腱驱动连续体机器人[14]

NOKOV 度量动作捕捉在研究中的应用摘录

2\. 信息采集模块
本文用到的信息采集设备是 4 台度量科技型号为 MARS1.3H 的摄像头如图 2-19 所示，该型号镜头的参数如图 2-20 所示。NOKOV 度量光学三维动作捕捉系统可实时进行动作数据采集。开发了丰富的 SDK、VRPN 接口工具，可以方便地将动作捕捉数据进行传输，支持进行二次开发。

引用格式 张治.基于软轴拉扭协同驱动的连续体机器人机构设计与控制系统研究[D].广西科技大学,2025.DOI:10.27759/d.cnki.ggxgx.2025.000159.

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面向重物搬运作业的柔性助力服研制

关键词

柔性助力服;外骨骼;搬运作业;动力学分析;力控策略;人机协同;

摘要

随着工业自动化与智能化的快速发展,重复的重物搬运作业在很多场景下仍然高度依赖人力,而长期高强度劳动易导致肌肉疲劳和慢性损伤,严重影响劳动者的健康和生产效率。尽管市场上已有多种搬运机械设备,但其灵活性不足,难以适应复杂或恶劣的作业环境。因此,研发一种能够有效提升人体搬运能力、缓解作业疲劳并降低肌肉损伤风险的助力装备具有重要的应用价值。外骨骼机器人作为一种可穿戴智能装备,已在医疗康复、工业生产和军事等领域展现出巨大潜力,但传统刚性外骨骼存在关节异构、穿戴舒适性差、额外能量损耗等问题,限制了其广泛应用。为解决这些问题,柔性外骨骼技术应运而生,其轻量化、贴合人体的特点为助力装备的发展提供了新的方向。本课题聚焦搬运作业场景,研制了一种融合上肢与下肢助力的全身柔性助力服,旨在通过降低搬运过程中的肌肉负荷和能量消耗,缓解长期高强度工作导致的疲劳和损伤。该柔性助力服采用拟人化机构设计,能够跟随人体完成行走、下蹲、搬运、起身等动作。课题首先基于人体工程学分析了搬运过程中的关键关节运动范围,为助力服的结构设计提供依据;随后将人体分为上肢和下肢两部分分别研究,设计出既可独立工作又可协同助力的柔性外骨骼系统。本体设计方面,设计了基于气压传感器的压力感知辅助搬运勾和以模块化驱动单元为核心的柔性助力服,建立了以树莓派为核心计算单元,STM32 为分节点和电机控制节点,基于 IMU 传感器、跟踪相机、气压传感器和拉力传感器的多传感器融合的硬件系统。本课题开发的柔性助力服自重仅 6.12kg,单驱动模块重量 0.81kg,最大助力负载达 10kg。在动力学分析方面,通过动作捕捉设备和 Open Sim 平台建立个性化人体模型,基于零力矩点和压力中心点设计单双足支撑相的判断逻辑,并利用逆动力学解算关键关节力矩,为助力服的力控提供数据支持。 在控制策略上,柔性助力服采用鲍登线缆驱动方式,结合拉力传感器的力反馈实现精确力控。针对系统惯性和摩擦问题,设计了动态调节和补偿算法,以优化人机协同效果。此外,基于动力学分析结果和压力感知辅助搬运钩,提出了高效的助力策略,确保在不同搬运任务中提供最佳助力。实验验证方面,采集负载搬运、搬运移动和持续搬运等任务中关键肌肉的表面肌电信号(s EMG)数据,结果表面助力服能够显著降低关键肌肉的激活程度,验证了柔性助力服在结构、硬件和控制策略上的有效性。 实验结果表明,所设计的柔性助力服能够有效减少搬运过程中的肌肉负荷和能量消耗,提升穿戴者的运动机能和工作效率。与刚性外骨骼相比,该柔性助力服具有更好的穿戴舒适性和人机协同性,解决了传统外骨骼的关节错位、额外能量损耗等问题。此外,其轻量化和模块化设计降低了制造成本,为物流运输、应急救援和军事应用等领域提供了经济实用的解决方案。本研究的成果不仅对缓解劳动力短缺问题具有现实意义,还为柔性外骨骼技术的进一步发展提供了理论和技术支持,具有显著的社会效益和研究价值。

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图 2-6　动补实验场景和软件显示界面

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2.2.2 人体搬运运动分析
为建立精准的人体运动学数据库以指导柔性助力服的本体设计，本课题采用光学动作捕捉系统对典型搬运动作进行运动学参数采集，由于人体搬运时，下蹲、搬运、放下过程的肢体运动范围明显大于正常步行时的范围，于是仅进行原地搬运的运动学信息采集实验。
Nokov 光学三维动作捕捉系统采用红外光学定位技术，通过布置在实验空间内的多个高速动作捕捉相机（采样频率可达 500Hz）实时追踪被动式反光标记点的三维坐标。系统硬件架构包含：1）高精度红外捕捉镜头 8 颗（分辨率 1280×1024）；2）千兆以太网 POE 供电分离器；3）六维测力台（量程±5000N，精度 0.1%）；4）信号放大器；5）网络交换机。配套的 XINGYING3.0 分析软件可实现：1）基于标记点云数据的人体骨骼模型自动重建；2）多刚体系统坐标系参数计算；3）关节角度、角速度等运动学参数的实时解算与可视化等功能。本课题使用该套系统进行关节运动数据采集。

引用格式　郭淞豪.面向重物搬运作业的柔性助力服研制[D].哈尔滨工业大学,2025.DOI:10.27061/d.cnki.ghgdu.2025.001537.

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https://kns.cnki.net/kcms2/article/abstract?v=yqBhao7Q9gzzoxCHs2KmxNd9ntuDsTEMmwU14g6SFE03jFdLk_Xs6puGamhzExYL0-xdut_nFklczrwAeK3agLckSVGT04hNLStztz6tJRoeapaOutUFrUDxBv8mXNMznpyoP_83gInytG7ccIJjC-w10QaSXvOmx3auJluhxL7w-Z4DISSkk0FvFS_Y2p-T&uniplatform=NZKP

新型刚柔混联连续体机器人运动建模

关键词

软轴;连续体机器人;运动静力学模型;神经网络;逆运动学;

摘要

针对一种新型软轴拉扭协同驱动的刚柔混联连续体机器人，开展了其运动建模研究。建立了基于分段恒曲率（PCC）并综合考虑多种载荷的运动静力学模型。为求解其高度非线性的逆运动学，构建了一种由牛顿-拉夫逊优化算法（NRBO）优化的反向传播（BP）神经网络模型（NRBO-BP模型）。实验结果表明，单/双段柔性体机器人末端弯曲角度平均误差分别为 4.2°和 7.1°;基于NRBO-BP 模型的轨迹跟踪最大位置误差为 2.5 mm，验证了所提方法的准确性与有效性。

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图 8　机器人样机与实验验证系统

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> *实验验证*
> *3.1 实验平台概述*
> *为验证所建模型与算法，搭建了图 8 所示的实验平台。该平台核心是感知系统:1 套空间定位精度为士 0.2mm 的光学动作捕捉系统(北京度量，NOKOV MARS1.3H)　用于获取末端位姿真值;6 个拉压力传感器(深圳锐力德，RDFTM10)串联于驱动链中,用于测量软轴输入牵拉力。所有实验均以机器人因重力产生的自然下垂状态为初始构型。*

引用格式　董佳祥,刘铨权,胡希平,等.新型刚柔混联连续体机器人运动建模[J].中国机械工程,2025,36(11):2678-2684.

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新型柔索驱动机器人的轨迹规划和运动控制

关键词

柔索驱动；混联机构；轨迹规划；模糊 PID；

摘要

传统刚性机器人随着应用领域的不断深入,逐渐显露弊端。为解决传统刚性机器人低负载自重比,价格成本高,人机协作性差的问题,本文基于柔索驱动的解决方案设计了一款新型机器人,并对此机器人进行机构设计、运动学分析、轨迹规划以及控制方案的设计,最终完成实验样机加工以及软硬件系统的搭建。首先,针对传统绳驱动串联机器人难以解耦的特点,设计了一种混联机构。在不减少自由度的同时,使用球面并联机构代替机器人手腕关节,以减少驱动机构到关节的传动距离,避免了关节之间的耦合。本文设计的新型柔索驱动机器人将驱动电机布置在远离关节的底座上,提高了负载自重比和人机交互安全性。结构上 3-DOF 串联机构确定了末端执行器的空间位置,3-DOF 并联机构确定了末端执行器的姿态。其次,为建立该机构的整体运动学模型。由于其结构的特殊性,可以采用先分开再整体的分析方法。先对串联机构使用 D-H 法建模,并通过带权重的最短行程原则求得其运动学逆解最优解,再根据同轴心球面并联机构(SPM)之间的约束关系建立其正逆运动学的模型,最后结合串、并联运动学分析之间的联系完成对整体运动学的分析。并对常用的轨迹规划方法进行分析和仿真,其中有空间(圆弧、直线)规划,多项式规划,三次 Bezier 三角样条规划,S(T)型速度曲线规划。再者,对机器人控制系统方案采用基于 PC 的控制方案,并完成硬件选型和软件控制系统的搭建。为解决传统伺服控制无法补偿伺服电机到执行元件之间误差这种半闭环控制的问题,结合机器人系统非线性时变的特点,设计了全闭环模糊 PID 控制策略,并结合 Twincat3 进行联合仿真,证明了该控制器拥有良好的控制效果。最后,在以上理论分析支持下,搭建机器人的软硬件实验平台,通过 NOKOV 运动捕捉系统捕捉末端轨迹,进行整体运动学实验和控制器性能对比实验。实验结果表明,该机器人整体运动学推导完全与实验结果一致。模糊 PID 控制较半闭环控制和传统 PID 控制的最大轨迹误差从 21.13mm 和 3.94mm 降低到 1.35mm。

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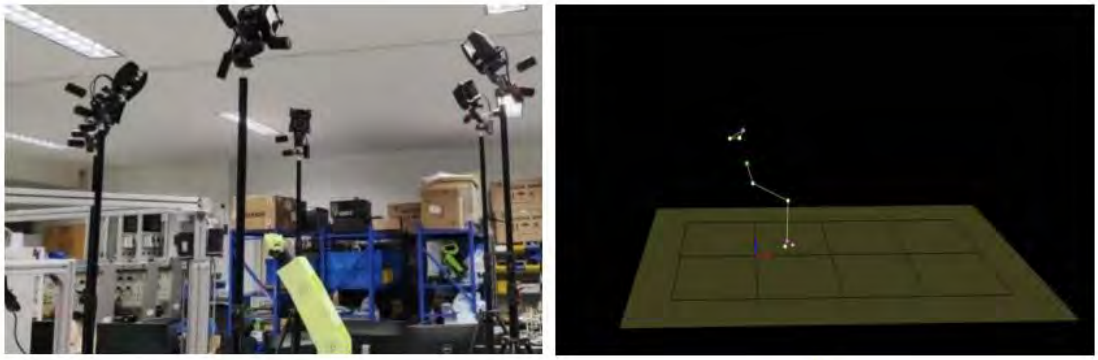

(a) (b)

图 5.10 Nokov 运动捕捉系统

Figure 5.10 The Nokov motion capture system

NOKOV 度量动作捕捉在研究中的应用摘录

为了获取到末端执行器的实际轨迹，本文采用的检测装置是 Nokov 运动捕捉 系统。该系统能够实现目标的精准定位，采用 FPGA 模块通过边缘计算快速处理 数据，支持多种数据采集和导出工作，操作简便易学习。其工作原理是光学镜头 发射红外光，红外光照射到反光标识点识被反射回镜头上的感应矩阵，多台相机 同时工作就可以解算出目标物体在空间中的位置、姿态等信息。本文采用 5 台相 机等间距围成一个圆形进行采集，具体布置如图 5.10(a)所示，(b)图中为 Cortex 软 件运行时的界面。其中得到的数据点位置等信息是在相机坐标系下，而相机坐标 系与实际机器人坐标系并不重合，因此需要对采集得到的数据进行转换。

引用格式 郑其祥. 新型柔索驱动机器人的轨迹规划和运动控制[D].合肥工业大学，2022.DOI：10.27101/d.cnki.ghfgu.2022.000766.

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一种可伸缩蛇形臂机器人的设计及运动学建模

关键词

蛇形臂机器人；结构设计；逆运动学；改进 FABRIK 算法；实验验证

摘要

蛇形臂机器人具有运动灵活和适应性强等优点，在非结构化和受限空间作业领域具有广阔 的应用前景。本文提出一种新型的蛇形臂机器人，其模块化关节具有主动的可伸缩自由度，增加了整机运动灵活性和复杂空间适应能力。建立了蛇形臂机器人的运动学模型，分析了驱动空间、关节空间 与末端操作空间的映射关系。特别针对关节具有伸缩自由度的构型特点，提出了两种关节-末端逆运动 学算法，即结合传统 FABRIK 算法与基于雅可比矩阵迭代法的组合算法和杆长迭代更新的改进 FABRIK 算法。为了验证两种算法的计算精度和效率，进行了数值仿真对比，结果表明两种算法均具有良好的 运算精度，改进的 FABRIK 算法具有更高的运算效率。最后，搭建了物理样机，并开展实验验证了所 提出蛇形臂机器人的运动性能。

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图 15　蛇形臂机器人样机

Fig.15 Prototype of the snake-like manipulator

图 16　基于动作捕捉系统的测量方案

Fig.16 Measurement scheme based on motion capture system

NOKOV 度量动作捕捉在研究中的应用摘录

基于蛇形臂机器人样机将开展运动性能实验，并采用 NOKOV 光学三维动作捕捉系统进行测量，系统最大测量误差为 0.2mm。如图 16 所示，为了同时测量位置和姿态，在每个关节单元末端设置了 3 个反光标志点，关节单元末端坐标系原点及姿态可由 3 个反光标志点中心位置求得。

引用格式 王旭浩,盛卧龙,吴孟丽,等.一种可伸缩蛇形臂机器人的设计及运动学建模[J/OL].中国机械工程,1-10[2025-09-16].https://link.cnki.net/urlid/42.1294.th.20250117.1154.009.

链接

https://kns.cnki.net/kcms2/article/abstract?v=6h6U53PWxNSXsllskBwdW2hCkzsx7L-zQqVsTlZvLHIfRjAQslwbuaGOb22kFMQKxJMxZ_LlkUn56OdcmS-04J-8woBUMOSOqMKoJHfYCZwpVbUK6fF5eAbNAegeO59yv1SD35xTstNJdj6RleVI8nh-o1LO09CCyA99UxW-4aKWuv4p-iXkbPX0Xjkke7S9&uniplatform=NZKP

用于丝驱动连续体机器人的实用运动学研究

关键词

丝驱动；连续体机器人；分段常曲率；粒子群算法；运动学

摘要

针对单段及多段连续体机器人运动学问题，提出分段常曲率与粒子群算法相结合的完整正逆运动学分析方法。以双段丝驱动连续体机器人为研究对象，首先设计含平移段的机器人样机；然后利用分段常曲率方法建立驱动空间与关节空间的相互映射，根据齐次变换得到关节空间至工作空间的正映射关系；最后利用线性递减权重粒子群算法实现工作空间至关节空间的逆映射。对双段连续体机器人的运动学进行仿真及逆运动学求解耗时测试，并在研制样机上进行了实验验证。仿真结果说明了所提运动学研究方法的合理性及逆运动学求解的快速性，实验结果显示位置平均误差小于双段连续体机器人本体长度的 6.22%，验证了所提运动学的有效性。

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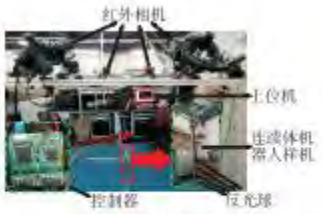

图 10 实验环境

Fig. 10 Experimental environment

NOKOV 度量动作捕捉在研究中的应用摘录

光学定位系统 Nokov 由八台红外相机、反光球和上位机组成，空间定位精度可达 ±0.1mm。将七个反光球分别固定于机器人末端及各段首尾及中间位置，定位系统可通过反光球获取末端实际位置和实际臂形。电控系统控制器采用 STM32 嵌入式处理器，用于控制与驱动丝相连的六个直流电机。

引用格式 陈元科，马飞越，向国菲等.用于丝驱动连续体机器人的实用运动学研究[J].计算机应用研究，2021,38（10）：3085-3088+3103.DOI：10.19734/j.issn.1001-3695.2021.03.0060.

链接

https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C44YLTlOAiTRKibYIV5Vjs7iy_Rpms2pqwbFRRUtoUImHdegf0IN1c8uQVyZSTckXLiwMhkyuIG0apn6Gknu4QaY&uniplatform=NZKPT

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VI. Medical Robot/Robotic Surgery

A comprehensive study on Mecanum wheel-based mobility and suspension solutions for intelligent nursing wheelchairs

Keywords

Intelligent nursing wheelchairs, Mecanum wheels, Mecanum wheel mobility chassis, Suspension mechanism

Abstract

Intelligent nursing wheelchairs significantly enhance mobility and independence for elderly individuals with disabilities. However, traditional designs often suffer from large turning radii that restrict their functionality in confined spaces. Addressing this critical challenge, this study introduces an innovative design utilizing a Mecanum wheel chassis that allows for omnidirectional movement, significantly improving maneuverability and stability. Our design incorporates independently controlled Mecanum wheels, overcoming traditional constraints and enhancing user autonomy. To address issues such as wheel spacing variations and hub center tilting, which can lead to slipping and inaccurate motion control, we developed a novel suspension system that stabilizes the chassis, minimizes slipping risks, and boosts motion control accuracy. Experimental validations, including shock absorption and positioning tests, demonstrate that our suspension system markedly enhances the wheelchair's control performance and stability, thereby providing users with enhanced precision and potentially improving their quality of life.

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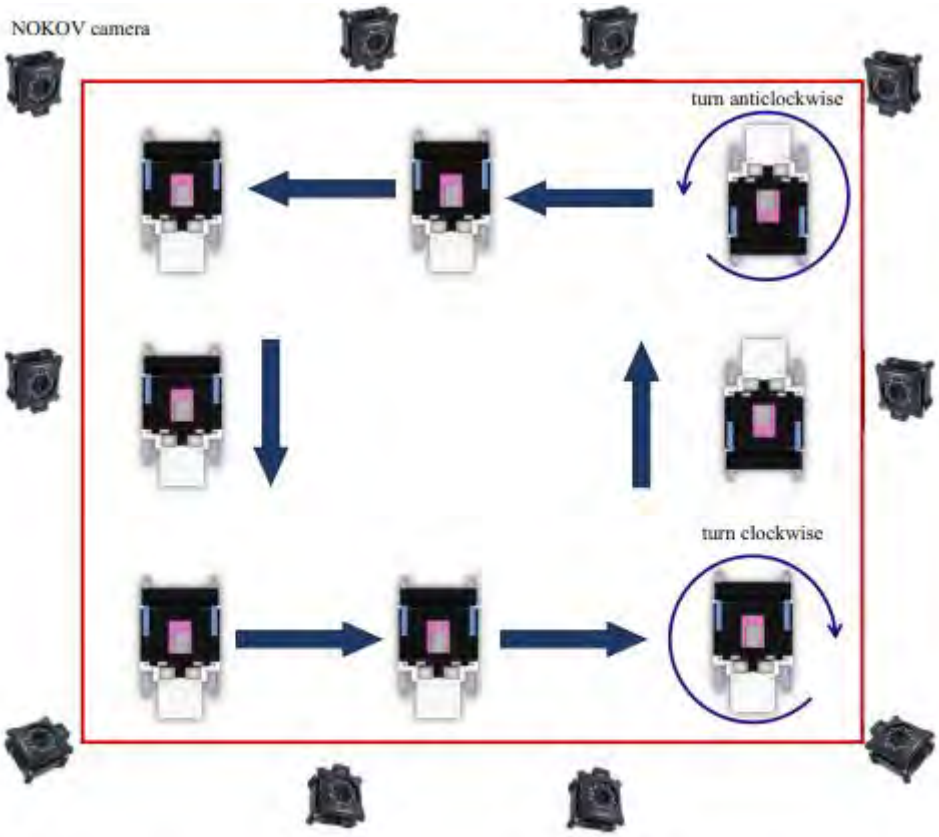

Fig. 11. Test the wheelchair movement trajectory with the NOKOV camera.

How NOKOV Contributes to the Research

We used a NOKOV camera device to capture the wheelchair's trajectory throughout the entire motion process and recorded it.

Citation Zhewen Z, Hongliu Y, Chengjia W, et al. A comprehensive study on Mecanum wheel-based mobility and suspension solutions for intelligent nursing wheelchairs[J]. Scientific Reports, 2024, 14(1): 20644.

Link https://link.springer.com/article/10.1038/s41598-024-71459-3

A Dual-Mode Robot-Assisted Plate Implantation Method for Femoral Shaft Fracture

Keywords

digitalization of surgical operation, dual-modesurgery, femoral shaft fracture, fracture plate implantation, robot-assisted surgery

Abstract

Background: Minimally invasive internal fixation is the preferred treatment option for femoral shaft fractures. However, there are problems such as invisibility, inaccuracy and instability in the process of plate implantation. Methods: In this paper, a dual-mode robot-assisted plate implantation method was proposed by combining a starting point determination algorithm, motion capture, deep learning and robotics. Results: The neural network model planned the plate implantation trajectory according to patient's condition. Then, the advantages of high stability and high precision of the robotic arm were used for plate implantation. Conclusion: The trend and fluctuation of the plate implantation trajectories obtained using this method met clinical requirements. Furthermore, the robotic arm implantation process was safe.

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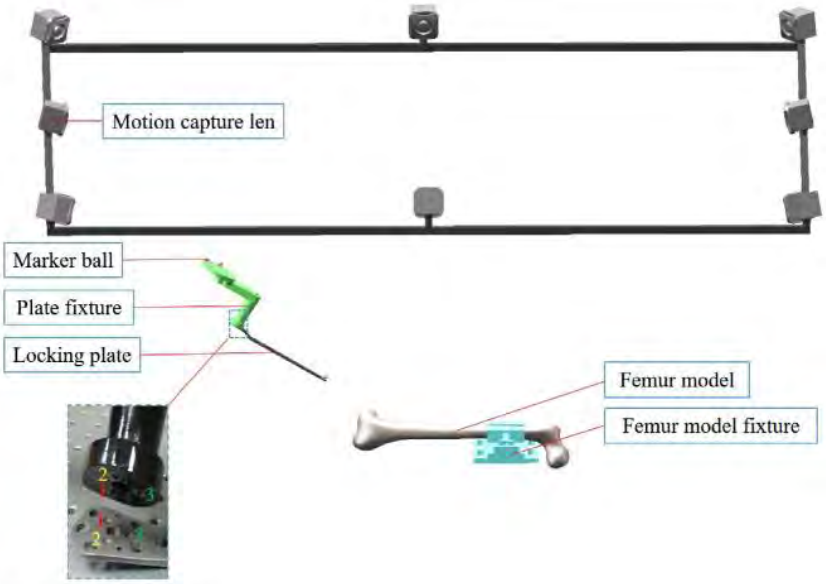

FIGURE 5 | Trajectory acquisition device.

How NOKOV Contributes to the Research

The plate fixture can be either hand-held or robot arm connected. The motion capture system is an eight-lens NOKOV optical three-dimensional motion capture system. After the plate is fastened to the plate fixture, three marker points are attached to it.

Citation Guo Y, Chen Y, Zhou X, et al. A Dual-Mode Robot-Assisted Plate Implantation Method for Femoral Shaft Fracture[J]. The International Journal of Medical Robotics and Computer Assisted Surgery, 2024, 20(6): e70008.

Link https://onlinelibrary.wiley.com/doi/10.1002/rcs.70008

A Home-based Dual-mode Upper Limb Rehabilitation System: Teleoperation Mode and Bilateral Mode with sEMG and IMU

Keywords

Upper limb hemiplegia, Exoskeletonassisted rehabilitation, Cloud-based telerehabilitation, Surface Electromyography (sEMG), Inertial Measurement Unit (IMU), Force feedback

Abstract

Upper limb hemiplegia is a common functional disorder among stroke patients, significantly affecting their quality of life. To address this issue, robot-assisted upper limb rehabilitation training has emerged as a new therapeutic approach, breaking through time and space limitations of traditional rehabilitation. Based on the above, a home-based dual-mode upper limb rehabilitation system is built, including teleoperation mode based on a cloud server and bilateral mode with fusion of Surface Electromyography (sEMG) and Inertial Measurement Unit (IMU). In the telerehabilitation mode, patients can receive professional guidance and regular training at home, greatly enhancing the accessibility of rehabilitation services. The experiments with the master side in Beijing City (China) and the slave side in three different cities are conducted through a cloud server. The slave side is controlled by the master side, and the contact force is sent back to the master side. In the bilateral mode, the intention of continuous movements across subjects can be accurately predicted via the fusion of sEMG and IMU, improving the naturalness of human-robot interaction. In the subject-independent modeling, the Root Mean Square Error (RMSE) under fusion showed a relative decrease of 15.0329% ($p < 10^{-4}$) compared to IMU data alone, and a significantly greater reduction of 61.9376% ($p < 10^{-4}$) in comparison with sEMG data alone. Robot-assisted upper limb exoskeleton, cloud-based teleoperation and bilateral training based on sEMG and IMU collectively form a new rehabilitation system, representing part of the future rehabilitation trend.

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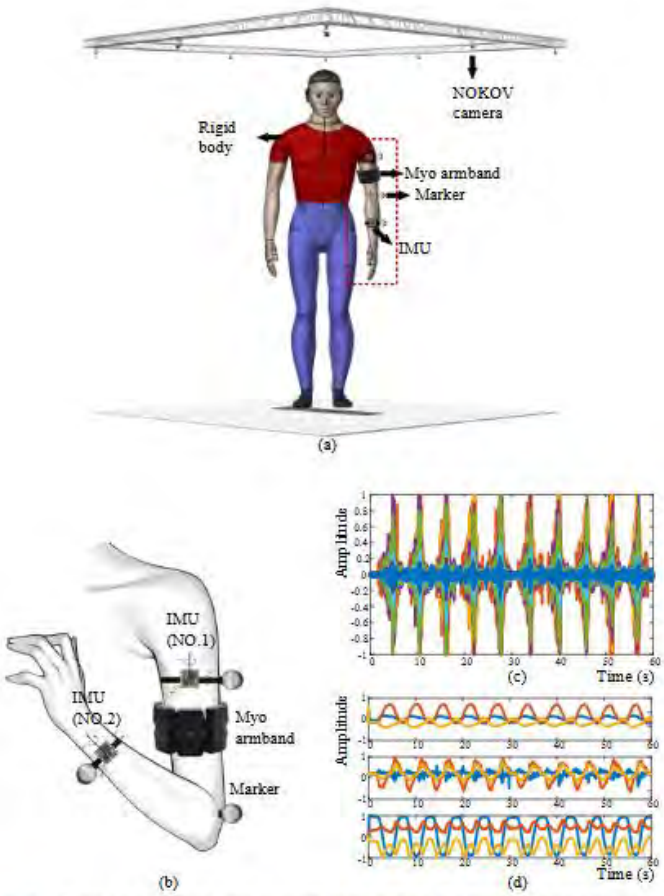

Fig. 6. Data acquisition. (a) overall acquisition diagram (b) upper arm with sEMG, IMU and marker (c) sEMG signal (d) IMU signal

How NOKOV Contributes to the Research

Fig. 6 illustrates the data acquisition setup. The sEMG data is acquired through the Myo armband (Thalmic Labs, Canada), which is worn on the left upper limb. The signal sample frequency of the Myo armband is 200 Hz. The IMU data is acquired through the JY901 (Witmotion, China), which is mounted on the left forearm. It adopts a Kalman dynamic filtering algorithm, enabling the rapid determination of the module's current real-time motion attitude. The signal sample frequency of the IMU is 20 Hz. For joint angle acquisition, the Mars visual capture camera (NOKOV, China) is used, which acquires the motion characteristics of the upper limb at asampling frequency of 200 Hz.

Citation Li H, Guo S, He R, et al. A Home-based Dual-mode Upper Limb Rehabilitation System: Teleoperation Mode and Bilateral Mode with sEMG and IMU[J]. IEEE Journal of Biomedical and Health Informatics, 2025.

Link https://ieeexplore.ieee.org/abstract/document/11079308

A Human-like Inverse Kinematics Algorithm of an Upper Limb Rehabilitation Exoskeleton

Keywords

rehabilitation robotics, exoskeletons, inverse kinematics, scapulohumeral rhythm

Abstract

Powered exoskeleton rehabilitation is an effective way to help stroke patients recover their motor abilities. Bionic structures and human-like control strategies can be used to enhance both the safety and efficacy of exoskeletons. However, the motion characteristics of the shoulder complex are not sufficiently considered. In this paper, we designed a 7-degrees-of-freedom (DOF) upper limb rehabilitation exoskeleton, FREE (functional rehabilitation exoskeleton). The mechanical structures of the shoulder and forearm of FREE are in accordance with human anatomy, and can be used to perform a wide range of synergistic motion of multiple joints while keeping a safe distance from the patient's head. A multiple-input-multiple-output (MIMO) shoulder girdle motion prediction model was developed to satisfy the synergy between humans and exoskeletons. Moreover, a constrained task priority and projected gradient-based inverse kinematics algorithm (CTPPG-IK) was proposed to achieve assistance with scapulohumeral rhythm. A motion capture system was used to collect different activities of daily life (ADL) motion data to validate the proposed algorithm. The experimental results show that the accuracy of the prediction model is higher than that of existing models, and the inverse kinematics algorithm can handle the end-effector task and joint space with a maximum angle error of 3.04×10−33.04×10−3 rad.

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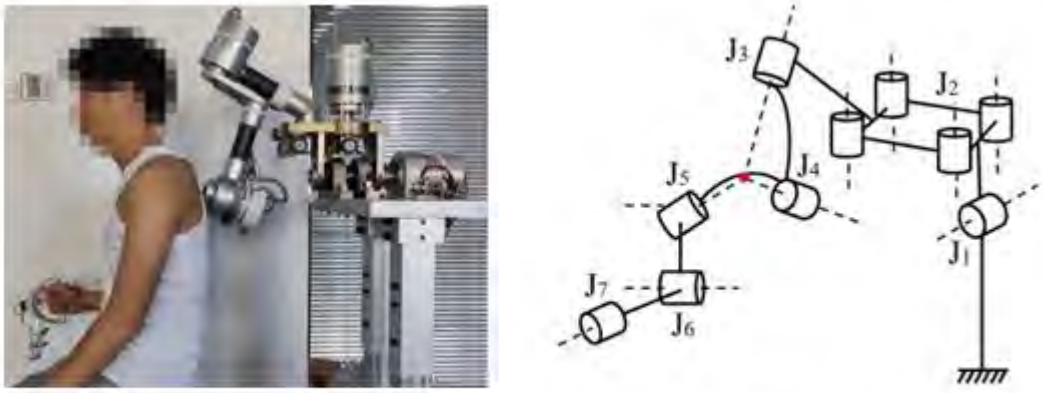

Figure 1. FREE exoskeleton prototype and its simplified model.

How NOKOV Contributes to the Research

An optical motion capture system with eight cameras (Mars2H, Nokov, sampling rate 60 Hz) was used to record the data of motions and reflectable marker points as the reference sensing method.

Citation Pei S, Wang J, Guo J, et al. A human-like inverse kinematics algorithm of an upper limb rehabilitation exoskeleton[J]. Symmetry, 2023, 15(9): 1657.

Link https://www.mdpi.com/2073-8994/15/9/1657

A Knowledge Transfer-Based Personalized Human–Robot Interaction Control Method for Lower Limb Exoskeletons

Keywords

Exoskeleton, personalized intent recognition, surface electromyography (sEMG), transfer learning

Abstract

Accurate intent recognition by patients while wearing exoskeletons is crucial during their rehabilitation exercises. In this article, a transfer learning framework for human-robot interaction (EMGTnet-KTD) is proposed to predict human movement intentions in human-robot interactions through surface electromyography (sEMG) signals. EMGTnet-KTD consists of a pretrained EMGTnet model and a knowledge transfer module. First, EMGTnet is designed based on a Transformer network. A temporal and spatial domain feature fusion module has been introduced on top of the Transformer network, and the inputs have been reconfigured to enable it to utilize the relationship between before and after human actions. In addition, the knowledge transfer module is composed of a feature extraction layer, a noise reduction layer, and the personalized human lower limb dynamics controller. To evaluate the effectiveness of the proposed method, an experimental validation of our self-collected dataset from seven subjects is performed. The results show that our method achieves better results than other continuous motion prediction methods. Finally, to validate that the generation angle conforms to human physiology, walking experiments involving the use of an exoskeleton are conducted. The experiments demonstrate the effectiveness of the proposed framework and its implementability for exoskeletons.

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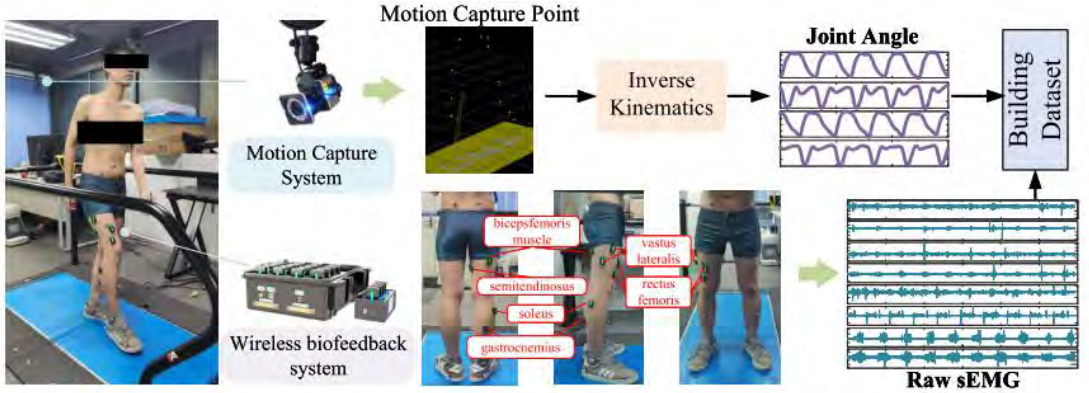

Fig. 1. Data acquisition experiment. Seven participants were recruited for the study and were outfitted with wireless sEMG sensors and passive markers. The participants were equipped with wireless EMG devices placed on major thigh muscles including the RF, LV, TA, BF, SE, and GA, while passive reflective markers were attached to specific anatomical locations such as the lumbar area, thighs, knees, calves, and feet for motion capture purposes.

How NOKOV Contributes to the Research

The data acquisition experiments are shown as Fig. 1. The continuous motion of the lower limb was recorded using a NOKOV motion capture system. The sEMG signals from the main lower limb muscles, including rectus femoris (RF), vastus lateralis (VL), tibialis anterior (TA), biceps femoris (BF), semitendinosus (SE), and gastrocnemius (GA), were also recorded with wireless biofeedback system (sampled as 2000 Hz).

Citation Yang M, Tian D, Li F, et al. A Knowledge Transfer-based Personalized Human–Robot Interaction Control Method for Lower Limb Exoskeletons[J]. IEEE Sensors Journal, 2024.

Link https://ieeexplore.ieee.org/abstract/document/10723275

A Robot-Assisted System for Dental Implantation

Keywords

computer systems, computer vision, engineering, mobile robots, pattern recognition

Abstract

For treating tooth defects or loss, dental implant technology is the main treatment method because of its comfort, beauty, durability and no damage to the adjacent teeth. Free-hand operation for dental implant surgery highly depends on the clinical experience of the doctors and their state during the operation. Moreover, the training period is long. Additionally, dental implant surgery guided by an implant guide plate also has some limitations, such as poor cooling effect, high chance of thermal burn injury to the bone, blind operation, inability to make real-time adjustments during the operation, etc. In this study, a robot-assisted dental implant implantation system guided by the NOKOV optical motion capture system is presented, and the functions of each component of the system is introduced. The kinematics of the system was analyzed, and the coordinate transformation between the optical motion capture system and the manipulator was completed. Finally, the motion planning of the manipulator was simulated according to the pose recognized by the optical motion capture system. The results of the simulation confirmed the effectiveness of the proposed robot-assisted system. Our findings suggested that the system should be further investigated for practical applications in the future.

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Fig. 3. NOKOV optical motion capture system

How NOKOV Contributes to the Research

In this study, an auxiliary implant placement system based on the NOKOV optical motion capture system was developed.
In this study, a NOKOV optical motion capture system was used (Fig. 3).
The relative pose relationship between the motion capture system coordinate system and the marker ball coordinate system OCT can be obtained by NOKOV.
Finally, based on NOKOV, the motion planning of the manipulator was simulated in the ROS.

Citation Wu X, Tang Q, Wang F, et al. A Robot-Assisted System for Dental Implantation[C]//International Conference on Intelligent Robotics and Applications. Cham: Springer International Publishing, 2022: 15-28.

Link https://link.springer.com/chapter/10.1007/978-3-031-13841-6_2

Adaptive control of the rehabilitation robot with the model uncertainty based on real human gait

Keywords

True human gait; Model uncertainty; Adaptive control; Rehabilitation robot; Structural parameters

Abstract

The lower limbs exoskeleton rehabilitation robot (LLERR) has been used widely in rehabilitation training of human lower limb injury, where the control research of LLERR is still a hot point in robotics. Therefore, in this paper, a trajectory tracking adaptive control based on human gait is proposed. Where, the real gait trajectory of human body mechanism by using NOKOV motion capture system is used in control system design. In the simulation results, the dynamics model uncertainty are also considered, and the real gait trajectory data of human body is used to the control system. According to the simulation results, when there is uncertainty in the LLERR model, the proposed trajectory tracking adaptive control method can improve the accuracy and reliability of the trajectory tracking, which makes it suitable for different patients. By adaptive control, the uncertain part of the LLERR is compensated, and the structure parameters of the robot are obtained

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How NOKOV Contributes to the Research

In this paper, the NOKOV motion capture system was used to collect the gait movement of the experimenter and obtain hip and knee trajectories. The sampling frequency of this test was 120Hz, and 70 groups were collected. The resulting trajectories of the hip and knee joints will be unsmooth and need to befiltered to obtain a smooth curve. The existingfiltering methods include least square method and Kalmanfilter, etc. In this paper, the least square method is used forfiltering. The NOKOV motion capture system combines with a pressure test bench to measure plantar torque, which can be calculated to obtain hip and knee torques, as shown in Fig3 and Fig4.

Citation Lu J, Aihui W, Ma Z. Adaptive control of the rehabilitation robot with the model uncertainty based on real human gait[C]//2020 International Conference on Advanced Mechatronic Systems (ICAMechS). IEEE, 2020: 282-285.

Link https://ieeexplore.ieee.org/abstract/document/9310078

Adaptive neural & fuzzy controller for exoskeleton gait pattern control based on musculoskeletal modeling

Keywords

mpaired gait, Exoskeleton, Sliding mode controller, RBF neuralnetwork, Fuzzy system, Minimum Learning Parameter

Abstract

The paper deals with the development of 2-link lower limb extremity manipulator for rehabilitation purposes in bio-medical engineering. The musculoskeletal modeling was performed on the collected human gait data to obtain the joint angles and driving force values for hip and knee movement. The results obtained from the proposed controller were verified using Matlab-Simulink. The robust adaptive RBF neural network and fuzzy sliding mode controller were developed to track the desired trajectory. The OpenSim software was utilized to perform inverse kinematics and inverse dynamics on the musculoskeletal model which is scaled according to the physical dimensions of the experimental subject. The simulation results stated that SMC-RBF network has better tracking rate, less chattering problems and handle unknown uncertainties well. Finally, the results obtained were compared with the existing method with the help of performance index parameters to prove their effectiveness.

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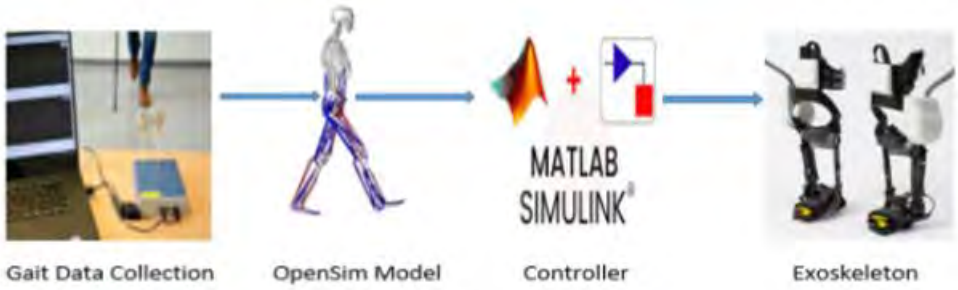

Fig. 1: Design for Lower Limb Exoskeleton

How NOKOV Contributes to the Research

3.2 Musculoskeletal modeling
To perform gait analysis data is collected first with the help of Nokov 3D motion capture system and force measuring plates. The proposed work has utilized data from \[10] to per.form gait analysis and rehabilitation. The gait represents the walking pattern behaviour of human beings, which is an important metric to predict human health in medical research\[43]. After the data was captured it was pre-processed by discarding or interpolating missing values \[44]. This data is then applied to a musculoskeletal model to obtain joint angles and torque values to perform rehabilitation therapy. Musculoskeletal model is an experimental model that helps to study motion, analyze and simulate it \[45l. It is a rich source of information that recreates human musculoskeletal to build exoskeleton in order to perform gait restoration after some injuries or strokes \[11]. Several software are available for musculoskeletal modeling namely OpenSim, MSMS, SIMM, LifeMOD and Anybody.

Citation Gupta A, Semwal V B. Adaptive neural & fuzzy controller for exoskeleton gait pattern control based on musculoskeletal modeling[J]. Multimedia Tools and Applications, 2024, 83(16): 49419-49439.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001098545500031

Adaptive Research of Lower Limb Rehabilitation Robot Based on Human Gait

Abstract

For patients with dyskinesia caused by central nervous system diseases such as stroke, the lower limb rehabilitation robot is required to provide passive rehabilitation training during the initial rehabilitation training, and a trajectory for healthy human body is used as a reference trajectory, this paper designs an adaptive controller to help patients with rehabilitation training methods. First, the gait trajectory of a healthy human body is obtained using an optical motion capture system and used as a reference trajectory for rehabilitation training. Then, the unilateral oscillating leg of the lower limb rehabilitation robot is modeled by dynamics. Based on this, an adaptive controller is designed to enable the lower limb rehabilitation robot to quickly track the desired trajectory, and a similarity function for evaluating the follow ability of the lower limb rehabilitation robot is proposed. Finally, experiments on the prototype of MATLAB simulation and lower limb rehabilitation robot demonstrates the feasibility of the proposed method.

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How NOKOV Contributes to the Research

Using the NOKOV 3D infrared passive optical motion capture system can only obtain the coordinates of the outside of the lower extremities of the human body. Therefore, the center position of each joint of the human lower extremity needs to be calculated based on the anthropometric experience formula to determine the walking parameters of the human body. Take the right lower limb of the human body as an example. The key points and world coordinates are shown in Fig.3. The positive direction is the direction of the human body as the axis, the positive direction of the axis is the left-hand side, and the positive direction of the axis is the vertical direction.For the hip joint of the right lower extremity of the human body, a local coordinate is established with the marker point 8, ie, the sacrum, as the origin, and the local coordinate unit vector is defined as,

Citation Yu J, Cai F, Wang A, et al. Adaptive Research of Lower Limb Rehabilitation Robot Based on Human Gait[C]//2018 International Conference on Advanced Mechatronic Systems (ICAMechS). IEEE, 2018: 86-92.

Link https://ieeexplore.ieee.org/abstract/document/8507128

An Upper Limb Exoskeleton Motion Generation Algorithm Based on Separating Shoulder and Arm Motion

Keywords

Upper-limb exoskeletons, human-like motion, scapulohumeral rhythm, inverse kinematics

Abstract

Many rehabilitation exoskeletons have been used in the field of stroke rehabilitation. Generating human-like motion is necessary for exoskeletons to help patients perform activities of daily living (ADL) while maintaining interaction quality and ergonomics. However, most of the current motion generation algorithms utilize inverse kinematics (IK) to solve the final configuration before generation, and do not consider the movement of shoulder girdle. Separately considering the shoulder girdle motion and arm motion, this paper proposes an algorithm integrated IK to generate human-like motion. The arm moves towards the target with a bell-shaped velocity in the absence of the final configuration, and the shoulder girdle maintain natural passive motion. Moreover, the generated motion can be mapped to the configuration space of exoskeletons. Compared with the experimental data collected using a motion capture system, the values of RMSE and HPDI of the generated wrist trajectory in the task space are within 0.2 and 0.17, respectively, while those of RMSE in the joint space are within 15 deg, which demonstrates the human-like nature of the generated motion.

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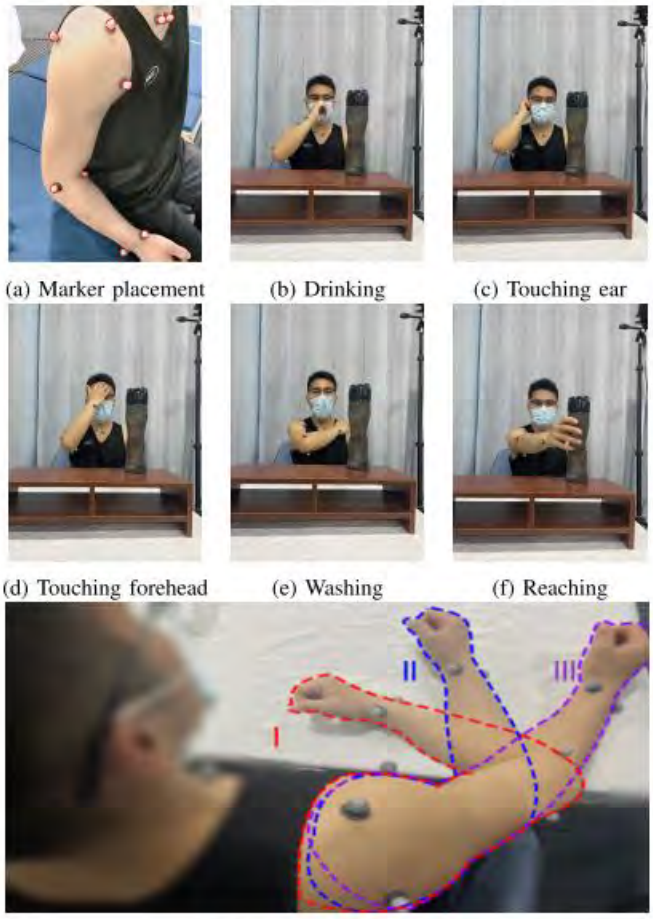

(g) Three start configurations

Fig. 4. Experimental protocol illustration.

How NOKOV Contributes to the Research

To train predictivemodels in section I, shoulder girdle kinematic data of healthysubjects were recorded using the same system. In order tocomplete the torso avoidance algorithm, the subjects' bodyinformation needs to be measured. The motion capture systemused consisted of 8 cameras (Mars2H, Nokov, sampling rate 60 Hz)and refective markers.

Citation Wang J, Pei S, Guo J, et al. An upper limb exoskeleton motion generation algorithm based on separating shoulder and arm motion[J]. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2024, 32: 1142-1153.

Link https://ieeexplore.ieee.org/abstract/document/10411099

Analysis of Motion Intention Prediction Based on Human Gait Data

Keywords

motion intention prediction, trajectory tracking, gait data, lower limb rehabilitation robot

Abstract

In the research of lower limb rehabilitation robotics, accurate prediction of human motion intention plays a key role in achieving active robot control, providing personalised rehabilitation programmes and enhancing training effects. Although there have been more studies on motion intention recognition methods based on physiological signals (e.g. EMG and EEG signals), there is still a relative lack of research on continuous motion estimation at multiple joint angles. To address this, a multi-objective gait prediction model is developed to simultaneously estimate the motion trajectories of the bilateral hip and knee joints. This model integrates joint position data obtained from the NOKOV motion capture system with a hybrid architecture combining convolutional neural networks (CNN) and long short-term memory (LSTM) networks. Experimental results demonstrate the model's capability to accurately predict joint motion trajectories, providing robust data support for the active control of lower limb rehabilitation robots, and highlighting its potential for practical implementation in rehabilitation training protocols.

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Fig. 1. Experimental platforms

How NOKOV Contributes to the Research

The gait trajectory acquisition equipment is the NOKOV 3D infrared passive optical motion capture system, which consists of eight optical infrared cameras, reflective marking points, calibration rods, data transmission equipment and Cortex software, and the experimental scene is arranged as shown in Figure 1.

Citation Duan H, Wang A, Gao S, et al. Analysis of Motion Intention Prediction Based on Human Gait Data[C]//2024 China Automation Congress (CAC). IEEE, 2024: 4949-4953.

Link https://ieeexplore.ieee.org/abstract/document/10865184

Assist-as-Needed Controller of a Rehabilitation Exoskeleton for Upper-Limb Natural Movements

Keywords

ehabilitation robotics, exoskeletons, assist-as-needed controller, physicalhuman – robot-interaction

Abstract

Active patient participation in the rehabilitation process after stroke has been shown to accelerate neural remodeling. The control framework of rehabilitation robots should provide appropriate assistive forces to users. An assist-as-needed (AAN) control method is proposed to help users to move upper limbs in the workspace freely, and to control the exoskeleton to provide assistance. The method is based on zero moment control (ZMC), helping the user achieve robotic traction with minimal interaction force. Based on the posture of the upper arm and forearm, an AAN controller can modify assistive forces at two human–robot-interaction (HRI) points along the direction opposite to gravity. A shoulder motion prediction model is proposed to enable the exoskeleton to mimic the user's upper limb natural movements. In order to improve the transparency during rehabilitation training, a nonlinear numerical friction model based on the Stribeck friction model is developed. A healthy adult male was recruited to perform various activities of daily living (ADL) tests to assess the effectiveness of the controllers. The experimental results show that the proposed ZMC controller has high HRI transparency and can control the exoskeleton to complete a wide range of upper limb movements, and the maximum interaction force and torque can be captured within −7.76 N and 4.58 Nm, respectively. The AAN controller can provide appropriate assistance in the desired direction, and the exoskeleton maintains kinematic synchronization with the user's shoulder during shoulder girdle movement.

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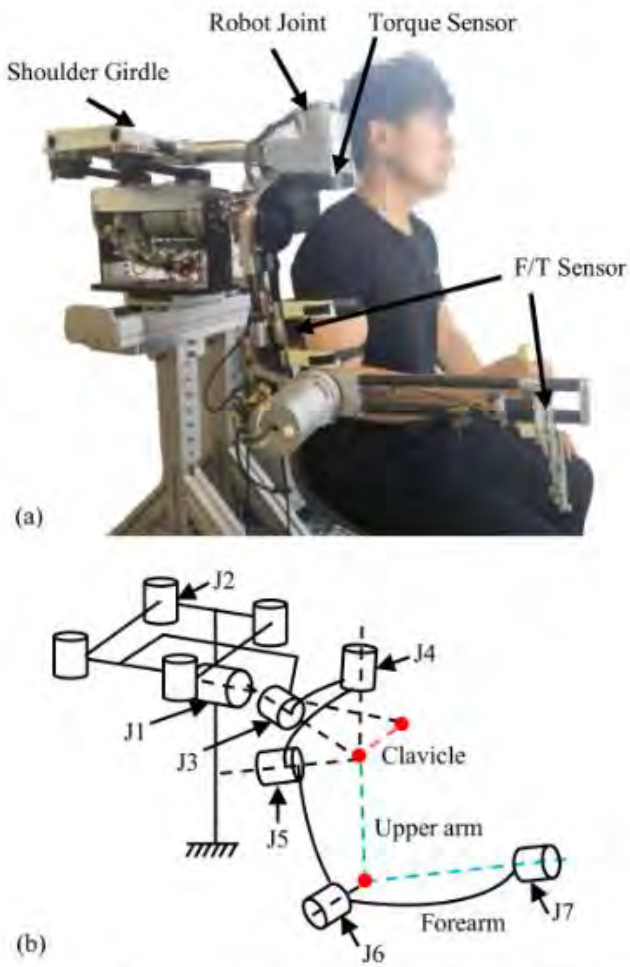

Figure 1. (a) FREE exoskeleton prototype. (b) FREE simplified model.

How NOKOV Contributes to the Research

Motion data of the volunteer's wrist in the global coordinate system were recorded using eight Mars2H and Nokov optical motion capture systems with a sampling rate of 60 Hz, employing reflective markers as the reference sensing method.

Citation Pei S, Wang J, Tian C, et al. Assist-as-Needed Controller of a Rehabilitation Exoskeleton for Upper-Limb Natural Movements[J]. Applied Sciences (2076-3417), 2025, 15(5).

Link
https://openurl.ebsco.com/EPDB%3Agcd%3A2%3A27062834/detailv2?sid=ebsco%3Aplink%3Ascholar&id=ebsco%3Agcd%3A183645307&crl=c&link_origin=scholar.google.com.hk

Augmented Reality-Assisted Robot Learning Framework for Minimally Invasive Surgery Task

Abstract

This paper presents an Augmented Reality (AR)assisted robot learning framework for Minimally Invasive Surgery (MIS) tasks. The proposed framework exploits an external optical tracking system to collect human demonstration. Gaussian Mixture Model (GMM) and Gaussian Mixture Regression (GMR) are utilized to encode and generate a robust desired trajectory for transferring to the real robot for the MIS task. The HoloLens 2 Head-Mounted-Display (HMD) is integrated for intuitive visualization of the robot configuration under the constraint of a small incision on the patient's abdominal cavity during the demonstration phase. Experiments are conducted to verify the feasibility and performance of the proposed framework and compared it with the kinesthetic teaching-based modality in a tumor resection MIS task. The results illustrate that the proposed AR-assisted robot learning framework requires lower workload demand, achieves higher performance and efficiency, and ensures the feasibility of the learned results for reproduction on a real robot for MIS tasks.

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How NOKOV Contributes to the Research

Tn addition, the passive observation-based modality is also a practical solution, including optical, electromagnetic tracking, etc [17]. Passive markers were attached to the surgical gripper and tracked by the Nokov motion capture device to collect the suturing skills from the human surgeon and transfer them to the physical robot [18]. Huang et al. designed a vision-based LfD framework for multi-robot cooperation and task reproduction in a robot-assisted bimanual sewing task, infrared markers were adopted to record human demonstrated trajectories [19]. Typically, the motion scaling and mapping strategy between the input device and the real robot should be properly established to ensure the effectiveness of human demonstration and robot reproduction [14].

Citation Fu J, Palumbo M C, Iovene E, et al. Augmented reality-assisted robot learning framework for minimally invasive surgery task[C]//2023 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2023: 11647-11653.

Link https://ieeexplore.ieee.org/abstract/document/10160285

Clustering of Human Motion Trajectory for Lower Limb Rehabilitation Robot Design Based on Machine Learning

Keywords

lower limb rehabilitation robots, machine learning, Gaussian distribution, hierarchical clustering, Gaussian process regression

Abstract

Lower limb rehabilitation robots, which usually produce repeated rehabilitative motion, not only simulate general human walking to help patients practice, but also do benefits to the remodel central nervous system to learn and store correct motion model. However, patients with different body parameters usually have different lower limb motion trajectories, and sometimes even the same person's multiple motion trajectories could differ, thus the task of designing a specific lower limb rehabilitation mechanism for the realization of every motion trajectory is not practical. In this paper, we propose an approach to the clustering of motion trajectories of human lower limb to obtain a limited number of rehabilitation task motion types. Firstly, Gaussian distribution is adopted for the fitting of multiple trajectories of the same person. Through comparison of various clustering algorithms according to separation and compactness, Hierarchical clustering algorithm is chosen to obtain the partitions of the clusters. Finally, the Gaussian process regression (GPR) model of each cluster is established. Results show that clusters generated by this approach can reflect motion trajectory of the subjects and predict human lower limb motion pattern. With a limited number of lower-limb motion patterns, the design task of rehabilitation robots could be greatly simplified.

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Fig 1 Reflective spots distribution on the participant (left) and cameras distribution (right)

How NOKOV Contributes to the Research

When the participant's one foot just leaves the ground, the Nokov motion capture system startrecording the motion trajectory, and it ends until thefoot touch the ground (in Fig.2), data is divided uniformly according to the step due to eliminating influence of velocity. Meanwhile, Cubic splineinterpolation is applied to connect discrete data point,and data is processed offline by the smooth filter. Thecoordinates of the motion trajectory are established by Homogeneous transformation.

Citation Zhao K, Teng Z, Gong N, et al. Clustering of Human Motion Trajectory for Lower Limb Rehabilitation Robot Design Based on Machine Learning[C]//ASME International Mechanical Engineering Congress and Exposition. American Society of Mechanical Engineers, 2019

Link
https://asmedigitalcollection.asme.org/IMECE/proceedings/IMECE2019/59407/V003T04A068/1072975?searchresult=1

Complete Gait Phase Recognition Based on Muscle Synergy Using PSO-CNN-LSTM Algorithm

Keywords

Convolutional neural network (CNN), gait phase recognition, long short-term memory (LSTM), muscle synergy, particle swarm optimization (PSO), stand-walk–stand walking cycle, surface electromyography (sEMG)

Abstract

Accurately recognizing gait phases, by applying proper instrumentation and measurement, is significant in walking rehabilitation training for patients with impaired mobility. In this study, seven phases of complete stand-walk–stand cycle as well as continuous daily walking were recognized based on muscle synergy and particle swarm optimization (PSO)-convolutional neural network (CNN)-long short-term memory (LSTM) model. First, the complete stand-walk – stand walking cycle was divided into starting phase, terminal swing phase, loading response phase, mid-stance phase, terminal stance phase, initial swing phase, and stopping phase, based on the features of surface electromyography (sEMG) collected by portable sEMG acquisition system and measured motion data of lower limb. Second, a muscle weight matrix and an activation sequence matrix were calculated by using nonnegative matrix factorization (NMF). Finally, a PSO-CNN-LSTM network was designed to recognize the complete stand-walk – stand cycle by applying the abovementioned matrices as input. Fourteen subjects volunteered to perform linear walking experiments under procedure to verify the feasibility of the proposed approach by comparing results with other classifiers and features. Experimental results show that the proposed approach was capable of achieving an average recognition accuracy of up to 85.384%. This work will offer a promising gait recognition method for rehabilitation robots to achieve natural and flexible human-robot interaction.

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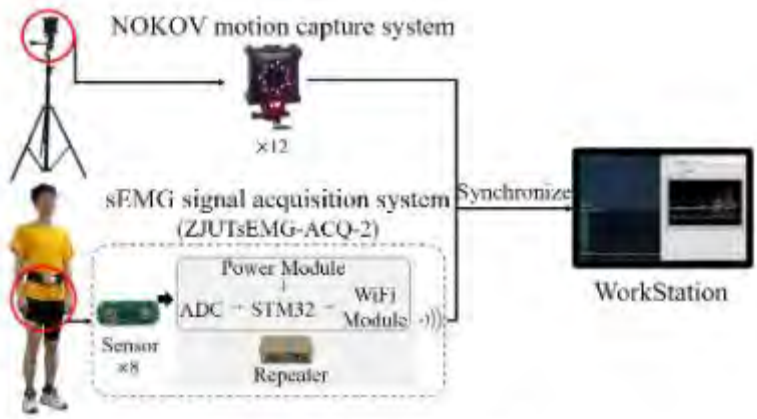

Fig. 5. Experimental setup.

How NOKOV Contributes to the Research

The optical motion capture system includes 12 NOKOV motion capture cameras Mars2H(NOKOV motion capture system, Beijing, China) and four reflective markers, which are placed on the tops and heels of both feet. The sampling frequency of NOKOV cameras is 100 Hz.

Citation Zhang K, Li X, Chen X, et al. Complete Gait Phases Recognition Based on Muscle Synergy Using PSO-CNN-LSTM Algorithm[J]. IEEE Sensors Journal, 2025.

Link https://ieeexplore.ieee.org/document/10948133

Control Design of Lower Limb Rehabilitation Robot Based on Gait Data

Keywords

Gait data, radial basis function (RBF) neural network, lower limb rehabilitation robot, 3D motion capture system, feedforward controlIntroduction

Abstract

In order to make the assisted rehabilitation training of the lower limb rehabilitation robot (LLRR)more consistent with human motor characteristics, and to provide more safe and effective rehabilitation training for patients with lower limb motor dysfunction, a control strategy of the LLRR based on human gait data and radial basis function (RBF) neural network is proposed. Firstly, the gait data of healthy human body acquired by 3D motion capture system is taken as the expected input of the system. Secondly, the RBF neural network adaptive controller generates the torque to drive the joint motion of the LLRR, so that the motion trajectory of the robot can track the desired trajectory. Then, the modified model based on feedforward control is used to compensate and correct the input torque of the robot, so as to achieve real-time correction and better tracking effect. Finally, the simulation results based on experimental data demonstrate the feasibility and effectiveness of the proposed method.

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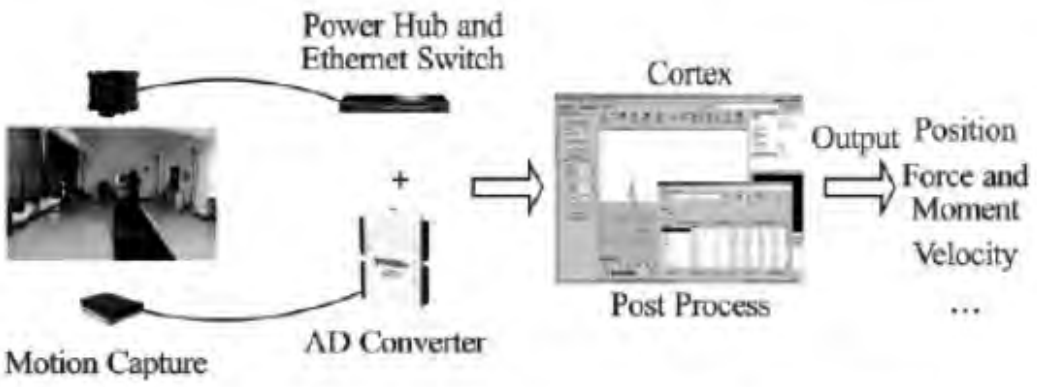

Fig. 2 Structure of Nokov optical 3D motion capture system

How NOKOV Contributes to the Research

The Nokov optical 3D motion capture system uses high-precision motion capture lenses to capture reflective Marker points, and constructs a motion acquisition and analysis system for 3D data. It is widely used in fields such as gait rehabilitation, motion analysis, and human-computer interaction. This article uses Nokov optical 3D motion use a capture system to collect human gait data for rehabilitation training.

Citation Sun L. Control design of lower limb rehabilitation robot based on gait data[C]//2024 IEEE 7th Information Technology, Networking, Electronic and Automation Control Conference (ITNEC). IEEE, 2024, 7: 486-491.

Link https://ieeexplore.ieee.org/abstract/document/10733224/

Control of Self-Balancing Lower Limb Exoskeleton for Various Wearers Under Dynamic Deformation

Keywords

Dynamic deformation, self-balancing exoskeleton, various wearers

Abstract

Unlike conventional lower limb exoskeletons that rely on external devices, the self-balancing exoskeletons enable individuals with diverse mobility impairments to regain the ability to walk. Current self-balancing exoskeletons struggle to balance between interpersonal adaption and compliance. Adjustments to parameters are often required when accommodating different wearers, and dynamic deformations pose significant challenges in the performance of these exoskeletons. This article proposes a control approach of self-balancing lower limb exoskeleton for various wearers under dynamic deformation, which includes two controllers. First, we propose a new informer-based feedforward deformation compensator, which could reduce the average position error and attitude error by 79.04% and 84.95%, respectively. Then, we design a compliance controller based on impedance control that can be applied to different wearers. At last, the self-balancing exoskeleton walking experiments with seven subjects (five male, two female) are conducted. The results reveal that this study achieves stable walking with the self-balancing exoskeleton loaded range from 0 to 73 kg.

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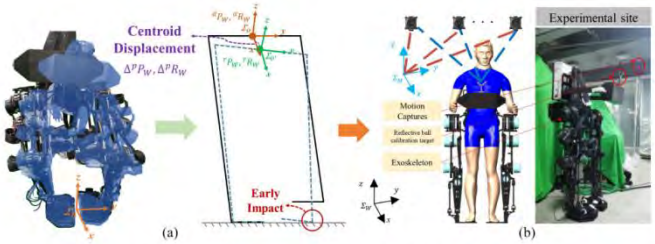

Fig. 1. Demonstration of deformation and the deformation measurement platform in the self-balancing exoskeleton robot. (a) Demonstration of deformation in the self-balancing exoskeleton robot, the major reason for deformation is the insufficient stiffness of the exoskeleton. The black line shows the desired state, the blue dashed line shows the real state. ${}^d P_W, {}^d R_W$ are the desired posture of the robot, and ${}^r P_W, {}^r R_W$ are the real posture of the robot because of the deformation. The deformation caused the centroid displacement $\Delta^p P_W, \Delta^p R_W$ and the early impact of the swing leg. (b) Self-balancing exoskeleton deformation measurement platform.

How NOKOV Contributes to the Research

To obtain the training dataset of Falong with the real pose of robotrTW, this study utilized a motion capture system NOKOV\[30], which is a high-performance device used for pre-cise capturing and collecting motion data of objects in 3-D space.As showninFig.1(b), the measurement coordinate system of the motion capture system was denoted as∑M, which is aligned with the world coordinate system∑W.

Citation Li J, Tian D, Li F, et al. Control of Self-Balancing Lower Limb Exoskeleton for Various Wearers Under Dynamic Deformation[J]. IEEE/ASME Transactions on Mechatronics, 2024.

Link https://ieeexplore.ieee.org/document/10665933

Cross-Activity sEMG-Driven Joint Angle Estimation via Hybrid Attention Fusion: Bridging Traditional Features and Deep Spatial Representations

Abstract

The growing prevalence of stroke necessitates advanced lower-limb exoskeleton control. This paper proposes HybridFusionAtt, a novel model for continuous joint angle estimation using surface electromyography (sEMG). Unlike conventional approaches, our framework uniquely integrates traditional time-domain features with CNN-extracted high-dimensional spatial features through an attention mechanism, where traditional features dynamically guide feature fusion as attention queries. The model was validated using data collected from eight participants performing four activities of daily living (walking, stair climbing, stair descending, and obstacle crossing). The proposed model achieves average \\(R^2 \\) values for knee and hip joint angle prediction of 0.8682 (walking), 0.8482 (obstacle crossing), 0.9294 (stair climbing), and 0.8676 (stair descending). Experimental results show that the proposed model significantly outperforms traditional LSTM and CNN-LSTM models in terms of accuracy and robustness, particularly in handling non-periodic actions such as obstacle crossing. The model achieves high performance by effectively fusing features and adaptively focusing on key features, enabling it to maintain robustness even under noisy conditions and significant individual differences. This demonstrates the model's broad application potential, especially in rehabilitation and prosthetic control systems.

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(a) Muscles position (b) Sensors (front) (c) Sensors (back)

Fig. 1: The positions of the selected muscles and the surface sEMG sensors

How NOKOV Contributes to the Research

EEight commonly used muscles in daily life were selected, including the rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), biceps femoris (BF), soleus (SL), medial gastrocnemius (MG), lateral gastrocnemius (LG), and tibialis anterior (AT). The muscle position can be referenced as shown in Figure 1a. The sEMG signals were acquired using a wireless acquisition system (Pico, Cometa, Italy), with a sampling frequency of 2000 Hz. The effect after attaching the sensors is shown in Figures 1b and 1c. To obtain joint angle data as labels for model training, joint angle information during movement is captured and calculated using an optical 3D motion capture system (NOKOV Motion Capture System, China), with a camera frame rate of 200.

Citation Z. Tang, X. Deng, Y. Wen, X. Han, J. Wu and Z. Yu, "Cross-Activity sEMG-Driven Joint Angle Estimation via Hybrid Attention Fusion: Bridging Traditional Features and Deep Spatial Representations," 2025 IEEE/RSJ International Conference on Intelligent Robot

Link https://ieeexplore.ieee.org/document/11247465

Design and Analysis of a Magnetic Anchored and Cable-Driven Surgical Forceps for Minimally Invasive Surgery

Keywords

magnetic surgical forceps; cable-driven; manipulator; control system

Abstract

Magnetic surgical instruments are primarily driven by magnetic force and/or micro-motors. When micro-motors are used to drive motion, they are typically installed near the manipulator joints, resulting in a larger manipulator size due to the presence of micro-motors. We designed a magnetic anchored and cable-driven surgical forceps, which separates micro-motors from the manipulator through cables. The cables are responsible for transmitting motion and force from micro-motors to the manipulator. This design enables the integration of relatively large motors (diameter: 8 mm) while maintaining a compact overall diameter of the manipulator (diameter: 10 mm). This is beneficial for improving the flexibility of the manipulator and facilitating the coordination between surgical instruments. The manipulator of the magnetic anchored and cable-driven surgical forceps has three degrees of freedom (DoFs): pitch, yaw and clamping. A magnetic attraction experiment was conducted to measure the magnetic force on the magnetic surgical forceps with the variation of abdominal skin thickness. The results indicate that at a distance of 20 mm, the magnetic force exerted on the magnetic surgical forceps is 5.86 N, with a maximum vertical load capacity of 5.13 N. Additionally, an ex vivo experiment was conducted to validate the practicality of the magnetic anchored and cable-driven surgical forceps prototype.

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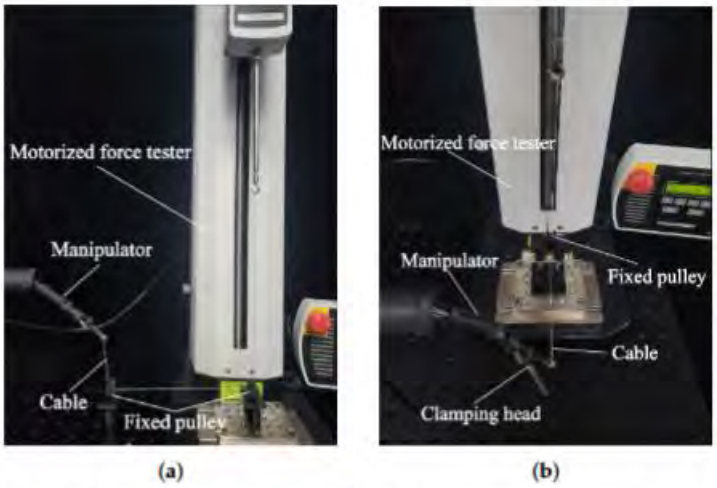

Figure 15. Experiments for testing the mechanical performance of the manipulator. **(a)** Experimental setup for measuring the lifting force. **(b)** Experimental setup for measuring the clamping force.

How NOKOV Contributes to the Research

4.3. Control of the Manipulator
The control method of the manipulator is detailed in Section 3. In this section, a seriesof experiments were conducted to evaluate the control performance of the manipulator'smotion. The experimental platform is shown in Figure 16. A motion-capture system(NOKOV) was employed to record the joint angles of the manipulator. The motion-capturesystem has a residual error of 0.15 mm. The control system of the manipulator is shown inFigure 16a. The markers attached to the manipulator are shown in Figure 16b. To facilitatethe identification of markers, the length of the surgical forceps head was extended from20 mm to 40 mm. The joint angles of the manipulator were calculated based on thecoordinates of the markers.Figure 16.Experimental setup for capturing the motion of the manipulator. (a) The control platformof the manipulator. (b) The deployment of the markers on the magnetic surgical forceps.The pitch joint was driven to rotate from 0° to 70° in increments of 10°. During theexperiment, due to motion errors, when the pitch joint was driven to rotate to 70°, the pitchjoint consistently reached its maximum deflection angle. So this position could not reflectthe control precision, and was excluded from the motion accuracy measurements for thepitch joint. When the yaw joint rotated to an angle greater than 40°, or less than−40°,the control precision decreased significantly. So the motion range of the yaw joint is limitedto−40° to 40° in practice.

Citation Li J, Li Y, Sun Z, et al. Design and Analysis of a Magnetic Anchored and Cable-Driven Surgical Forceps for Minimally Invasive Surgery[J]. Micromachines, 2025, 16(10): 1109.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001601977100001

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Design and analysis of human-machine compatibility of an end-traction ankle rehabilitation robot based on IMU and MoCap

Keywords

Inertial Measurement Unit, Motion Capture System, Human-Machine Compatibility, Kinematic characteristics, Ankle Rehabilitation Robot

Abstract

The discrepancy between the human ankle center of rotation (H-CoR) and the robot center of rotation (R-CoR) during rehabilitation training with an ankle rehabilitation robot (ARR) can result in reduced training efficiency, poor human-machine compatibility, and even secondary ankle injuries. To address this issue, a serial equivalent fitting model of the eccentric UR mechanism is established, and the kinematic characteristics of the ankle joint are analysed using an Inertial Measurement Unit (IMU) and a Motion Capture (MoCap) system. Based on the kinematic analysis result, a human-machine compatible design methodology for the end-traction ankle rehabilitation robot (ETARR) is proposed. The ETARR model prototype is designed, and both the IMU-based data acquisition and vision-based ankle motion capture system are developed to perform spatial and slip analyses of ankle motion, respectively. Rehabilitation training experiments show that, compared with platform and wearable ARRs, the proposed ETARR features a structurally simple and flexible design with superior human–machine compatibility, making it a promising solution for ankle rehabilitation training.

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Fig. 4. Motion capture experiment site.

How NOKOV Contributes to the Research

4\. Joint motion slip analysis of AJC
4.1.Motion capture design of experiments
Since the IMU cannot capture detailed motion information of the ankle joint, and the Mocap system provides higher measurement accu-racy \[29], the motion test was conducted using the Mocap system to obtain precise data on the ankle joint's movement. The NOKOVMoCapsystem is an optical 3D MoCap system capable of capturing motion data of human objects. Based on computer vision algorithms and the ste-reoscopic layout of multi-camera, it can achieve omnidirectional tracking and capture the target feature points of moving objects. The system consists of the NOKOV MARS series of cameras, operating soft-ware, reflective spheres, and calibration rods. Generally speaking, the more cameras a Mocap system has, the higher the accuracy of the ac-quired reflective sphere coordinates. However, too many cameras will substantially increase the resulting cost, computational complexity, and the difficulty of spatial layout will also increase accordingly. After careful consideration of the AJC's small amplitude movements, twelve cameras were selected. Fig. 4displays the test site setup.

Citation Wang W, Dong B, Zhang W, et al. Design and analysis of human-machine compatibility of an end-traction ankle rehabilitation robot based on IMU and MoCap[J]. Sensors and Actuators A: Physical, 2025: 116887.

Link https://webofscience.clarivate.cn/wos/alldb/full-record/WOS:001541129900002

Design and Evaluation of an Omnidirectional Wheel-Driven Endoscope-Assisted Robotic System Based on Motion Capture Control

Keywords

endoscopic assist robot, master-slave control, motion capture, omnidirectional wheel

Abstract

Background: In endoscopic surgery, surgeons collaborate with assistants to manipulate the endoscope and instruments, making it impossible to perform the surgery independently. Methods: We propose an endoscopic assistive robot based on motion capture control, enabling surgeons to control the endoscope with one hand. The system uses cameras at the master end to capture real-time motion information from the marker accessory, determining the surgeon's intent. It then controls the robot at the slave end to simulate surgical delivery actions, enabling precise endoscopic positioning through master-slave mapping. The omnidirectional wheel design addresses coupling issues of traditional friction wheels, significantly improving control accuracy. Results: Testing demonstrated a maximum delivery error of 3.99% and 45.77% improvement in rotational precision. The system received positive feedback in both simulated and animal trials. Conclusions: The system empowers surgeons to perform endoscopic procedures independently, establishing a foundation for advancing diagnosis and treatment of gastric diseases.

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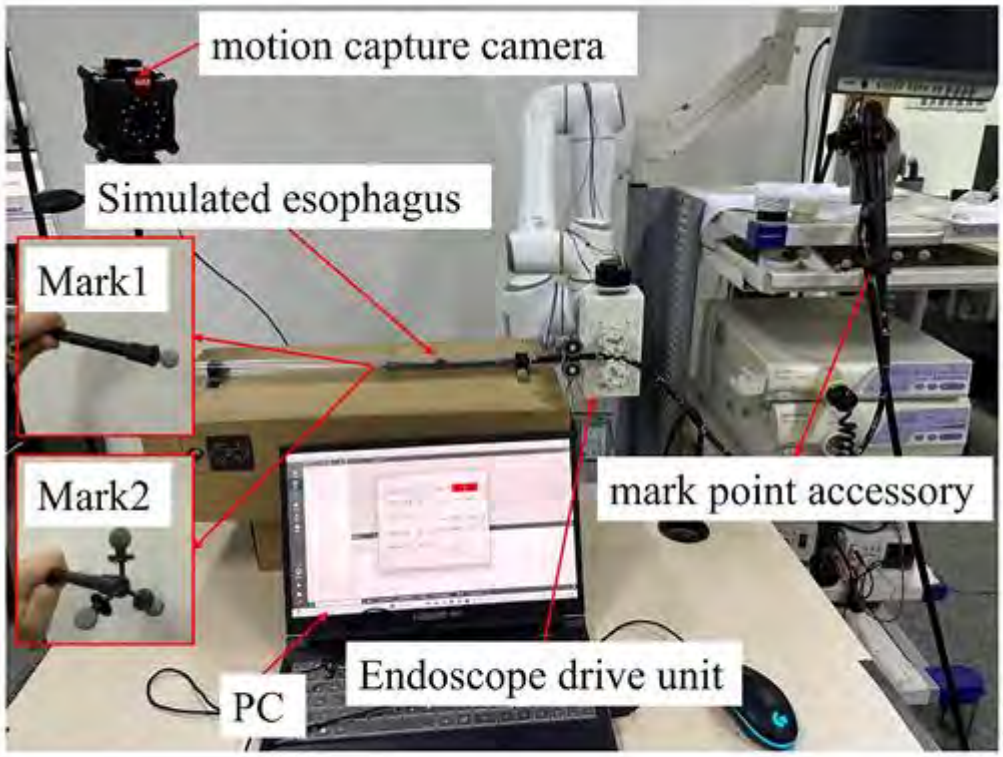

FIGURE 9 | Simulated oesophagus surgical platform for relevant experiments.

How NOKOV Contributes to the Research

A simulated oesophagus surgical platform for relevant experiments was constructed to validate the effectiveness of the endoscopic-assisted robotic system. The experiments employed NOKOV motion capture system to measure the delivery displacement and rotational angles of the distal end of the endoscope. Pose information was captured at the endoscopic distal markers 1 and 2 through camera detection of reflective markers. We removed all other reflective objects from the experimental area beforehand to prevent extraneous reflective points from interfering with the data.

Citation Yu X, Chen Y, Shi B, et al. Design and Evaluation of an Omnidirectional Wheel-Driven Endoscope-Assisted Robotic System Based on Motion Capture Control[J]. The International Journal of Medical Robotics and Computer Assisted Surgery, 2025, 21(3): e70070.

Link https://onlinelibrary.wiley.com/doi/10.1002/rcs.70070

Design and Performance Analysis of a Series-Parallel Self-Aligning Index Finger Exoskeleton

Keywords

Kinematic compatibility analysis, self-aligning index finger exoskeleton, series-parallel mechanism

Abstract

Hand exoskeletons have become increasingly crucial for the rehabilitation of hand function, as relevant studies have shown that using the exoskeletons to assist in rehabilitation training can improve hand motor function. However, developing a human-robot kinematic compatibility exoskeleton while providing sufficient assistance torque is still a challenge. This letter develops a series-parallel self-aligning index finger exoskeleton to assist the index finger in flexion/extension and adduction/abduction training. A series-parallel mechanism driven by two motors simultaneously was proposed for the metacarpophalangeal (MCP) joint, which can ensure human-robot joint axes self-alignment and increase the joint assistance torque. A kinematic compatibility analysis method was proposed, and the kinematic compatibility of the series-parallel mechanism was analyzed. The degrees of freedom and forward kinematics of the proposed mechanism were analyzed, and its workspace was calculated, which results show that the motion range of the MCP joint can meet the grasping training requirements. Preliminary experiments were carried out, and the results indicate that the motion trajectory coefficients of the marker points at the MCP, PIP, and DIP joints averaged for all subjects with and without the proposed exoskeleton are 0.993, 0.956, and 0.939, respectively, which can verify the kinematic transparency of the proposed mechanism. The assistance torque generated by the proposed mechanism on the MCP joint can meet the joint assistance torque requirements. In a word, the proposed exoskeleton can achieve flexion/extension and adduction/abduction training, human-robot joint axes self-alignment, and provide sufficient assistance torque.

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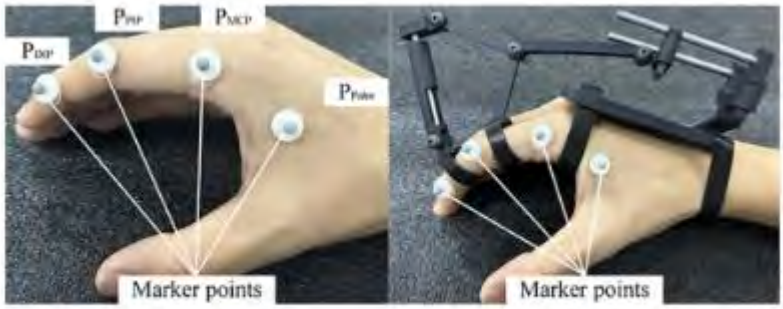

Fig. 7. Experimental setup of the index finger exoskeleton with the motion capture marker points.

How NOKOV Contributes to the Research

In this experiment, the proposed exoskeleton's kinematic transparency tests were conducted with and without the exoskeleton to evaluate whether the exoskeleton affects the natural movement of the index finger. An optical motion capture system (MARS2H, NOKOV, CHN) equipped with eight high-speed cameras was used to record the movement data of the index finger joints. The system's sampling frequency is 200 Hz, and the average accuracy of reconstructed marker coordinates is 1.5 mm. Four markers were placed on one side of the index finger: three markers on the outer side of the DIP, PIP, and MCP joints (PMCP, PPIP, PDIP), and one marker on the back of the hand near the thumb as the reference point (PPlam), as shown in Fig. 7.

Citation Sun N, Wang Z, Cheng L, et al. Design and Performance Analysis of a Series-Parallel Self-Aligning Index Finger Exoskeleton[J]. IEEE Robotics and Automation Letters, 2025.

Link https://ieeexplore.ieee.org/document/10982040

Design of a Portable Biofeedback System for Monitoring Femoral Load During Partial Weight-Bearing Walking

Keywords

Femoral loading, rehabilitation, weight bearing, wearable sensors, deep learning, gait monitoring

Abstract

Patients with femoral fractures are typically advised to undergo partial weight-bearing (PWB) gait training during the postoperative rehabilitation period to facilitate bone healing and restore lower limb function. Various current portable biofeedback devices monitor ground reaction force (GRF) to assess the femoral loading of patients with fractures during PWB walking. However, due to the influence of muscle forces and the complexity of load transmission in the lower limbs, GRF may not accurately reflect the internal forces in the femur during walking. In this study, we developed an innovative biofeedback device that incorporates inertial measurement units and pressure-sensitive insoles. Utilizing data collected from 12 participants, a physics-informed temporal convolutional network (PITCN) method was proposed to estimate the internal femoral loading. The performance of the PITCN method was compared with two other machine learning approaches and a baseline method, demonstrating superior predictive capabilities. The study also revealed that, irrespective of the weight-bearing level during walking, the peak femoral loading consistently exceeded the peak GRF. Moreover, the timing of the peak values for these two forces within each gait cycle may not always coincide. These findings further emphasize the necessity of monitoring and providing feedback on the actual femoral loading, rather than solely relying on GRF, during PWB gait training for patients with fractures. The developed system is a non-invasive, reliable, and portable device that provides audio feedback. It shows potential as a viable solution for gait rehabilitation training in daily life, contributing to the enhancement of patients' rehabilitation outcomes.

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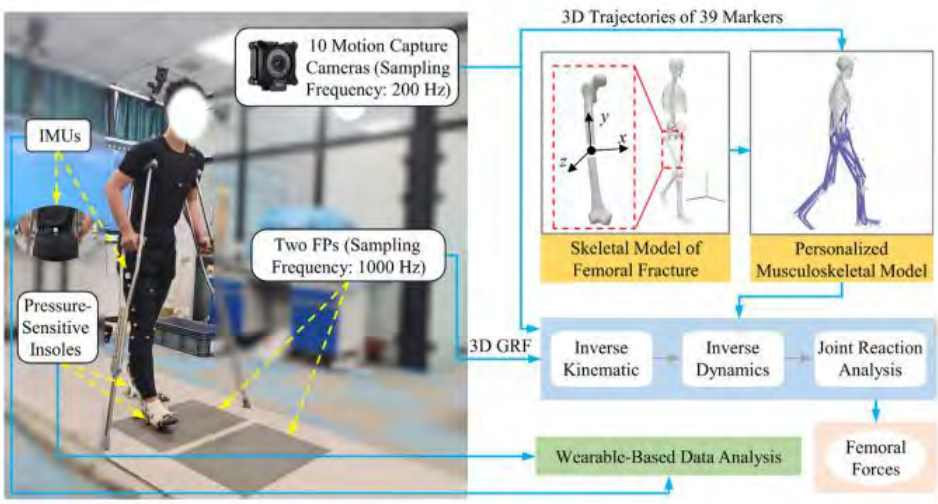

Fig. 3. Experimental data collection for lab-based and wearable-based data analysis.

How NOKOV Contributes to the Research

On the day of the experiment, 39 retro-reflective markerswere placed on each participant's body. Ten motion capture cameras (Nokov, Beijing, China) and two force plates (Bertec,Ohio, USA) were used to record the participants' marker trajectories and 6-axis GRF during walking, respectively.

Citation Ma T, Fan T, Xu X, et al. Design of a Portable Biofeedback System for Monitoring Femoral Load During Partial Weight-Bearing Walking[J]. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2025.

Link https://ieeexplore.ieee.org/abstract/document/10879047

Design of Wearable KOA Postoperative Rehabilitation Training Equipment

Keywords

Knee joint assistance, Wearable exoskeleton, Rehabilitation training, Innovative design

Abstract

Knee Osteoarthritis is one of the main knee joint diseases, severely affecting normal body movement and daily life. This article aims to improve the rehabilitation effectiveness in the later stages of recovery for patients by designing a wearable postoperative rehabilitation training device. Firstly, human gait data will be collected using motion capture devices, and the trajectory of the human gait will be analyzed. Secondly, based on the postoperative rehabilitation needs of patients, an innovative design of wearable rehabilitation training device will be developed. This device will utilize ankle joint movements to drive mechanisms that can provide resistance training and walking assistance, aiming to achieve the goal of assisting in the rehabilitation process. Finally, experimental validation will be conducted using motion capture devices to demonstrate the feasibility of this device. This will provide valuable data and evidence for the development of lower limb assistive rehabilitation devices in the future.

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How NOKOV Contributes to the Research

In this study, we used the NOKOV degree-of-freedom optical 3D motion capture system to collect raw data on human gait. We gathered data on knee joint angles without wearing any rehabilitation assistive devices. This data was analyzed to identify the patterns and characteristics of human gait, which served as the found ationfor the design of the rehabilitation training device.

Citation Wang X, Lin W, Zhao J, et al. Design of Wearable KOA Postoperative Rehabilitation Training Equipment[C]//ICMD: International Conference on Mechanical Design. Singapore: Springer Nature Singapore, 2023: 469-483.

Link https://link.springer.com/chapter/10.1007/978-981-97-0922-9_30

Determination of Knee and Ankle Trajectories and Synthesis of Four-Bar Linkage for Rehabilitation

Keywords

Rehabilitation, Trajectories, Passive markers, Four-bar mechanism, Path generation

Abstract

In movement-dependent control applications like rehabilitation, real-time gait cycle identification is essential to develop any supporting mechanism. In this paper, ten healthy subjects are considered to analyze the gait, and trajectories have been determined and compared. Video recording and passive markers-based technique have been implemented. Gait cycles for healthy subjects have been extracted from Kinovea software and comparison has been made among all the detected trajectories to draw the range of trajectories. The average curves for knee and ankle trajectories have been found to synthesize a four-bar mechanism. This synthesis problem is formulated for the knee trajectories that support the whole gait cycle while walking on horizontal plane.

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Fig. 3 Ankle and knee trajectories developed using Kinovea software. **a** Ankle trajectory. **b** Knee trajectory

(a). Ankle Trajectory.

(b). Knee Trajectory.

How NOKOV Contributes to the Research

The NOKOV optical motion capture system including cameras, multiple markers, and a master computer utilized allowing the motion capture system to collect data on moving object's displacement \[14]. It is important to understand and quantify the motion of the human knee joint before proceeding to design an artificial one which mimics it \[15]. The trajectories designed, provided by the department of Health and Human Performance by measuring 29 healthy female and 33 healthy male individuals walking slowly were determined using a VICON photogrammetry system \[16].

Citation Singh G, Chaudhary H, Singh R. Determination of Knee and Ankle Trajectories and Synthesis of Four-Bar Linkage for Rehabilitation[C]//International and National Conference on Machines and Mechanism. Singapore: Springer Nature Singapore, 2023: 61-70.

Link https://link.springer.com/chapter/10.1007/978-981-97-5423-6_6

Development of Robotic Ankle–Foot Orthosis With Series Elastic Actuator and Magneto-Rheological Brake

Keywords

Ankle-foot orthosis, robot-assisted therapy, energy harvesting, magneto-rheological effect, torsion spring, actuators and transmissions, mechanism design, wearable robots

Abstract

This paper illustrates the development and experimental validation of a robotic ankle-foot orthosis (AFO) with a series elastic actuator (SEA) and a magneto-rheological (MR) brake. First, the biomechanics of a human ankle joint during walking is explained. Next, the hardware design of the robotic AFO is introduced, including its mechanical structure, actuator design and configuration, and electronic system. The SEA is primarily composed of an electric motor, a planetary gearbox, a torsion spring, and a pair of bevel gears. The MR brake can modulate the viscosity of the robotic AFO and generate a large braking torque of 21.8 Nm with a low power of 8.8 W. Additionally, the modeling of the robotic AFO is presented, followed by an introduction to its control; several gait evaluation indices are proposed as well. Finally, a pilot study is conducted to verify the effectiveness of the developed robotic AFO. The experimental results demonstrate that the robotic AFO has the potential to provide dorsiflexion assistance, thus preventing foot slap and toe drag, in addition to plantarflexion assistance for the forward propulsion of the body. During a gait cycle, an average power of 0.23 W is harvested, and an 8% improvement in the system energy efficiency is achieved.

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How NOKOV Contributes to the Research

In the first walking experiment, the participants walked without the robotic AFO with a normal gait pattern. The kinematic data of the participants' ankle joints were obtained using a motion capture system (NOKOV, Beijing Nokov Science & Technology Co., Ltd., China). In the second, third, and fourth walking experiments, the robotic AFO was worn on the left foot of the participants, and the sensors of the robotic AFO were used to measure the motion data of the human–AFO system. For a fair comparison, the motor energy harvesting mode was not utilized in the third walking experiment. In each walking experiment, 12 steps were extracted from each participant.

Citation Chen B, Zi B, Wang Z, et al. Development of robotic ankle–foot orthosis with series elastic actuator and magneto-rheological brake[J]. Journal of Mechanisms and Robotics, 2021, 13(1): 011002.

Link https://asmedigitalcollection.asme.org/mechanismsrobotics/article-abstract/13/1/011002/1086017/Development-of-Robotic-Ankle-Foot-Orthosis-With

Estimation of Gait Phase of Human Stair Descent Walking Based on Phase Variable Approach

Keywords

Wearable robotics, prosthetics and exoskeletons, intention recognition, gait phase estimation, stair descent

Abstract

Synchronization between a wearer and a lower limb powered prosthesis is important for effective control. Typically, phase variable-based phase estimation methods are employed. However, there is a noticeable lack of studies focusing on estimating the gait phase during stair descent, likely due to the difficulty in generating a reliable phase variable. In most studies, the thigh angle is used to generate phase variables for level walking because it follows a sinusoidal pattern. However, during stair descent, the thigh angle exhibits only a partially sinusoidal shape, making it challenging to apply the methods used for level walking. In this study, we propose a novel phase variable generation method to address the difficulty of using only the thigh angle for stair descent. To estimate the gait phase reliably, the phase variable is defined differently for the stance and swing phases: the hip position is used to generate the phase variable during the stance phase, and the thigh angle is used during the swing phase. These phase variables are then unified into a single phase variable (PV-ENT) for the entire gait cycle of stair descent. During this unification process, a non-smooth transition occurs around the phase transition point. To address this, a blending method is applied. The proposed method was validated using the data from 12 healthy subjects, collected through a motion capture system and IMU sensors. The results demonstrate a reliable phase estimation performance. Moreover, the blending method successfully improves the smoothness of the phase variable around the phase transition point without reducing the overall phase estimation performance.

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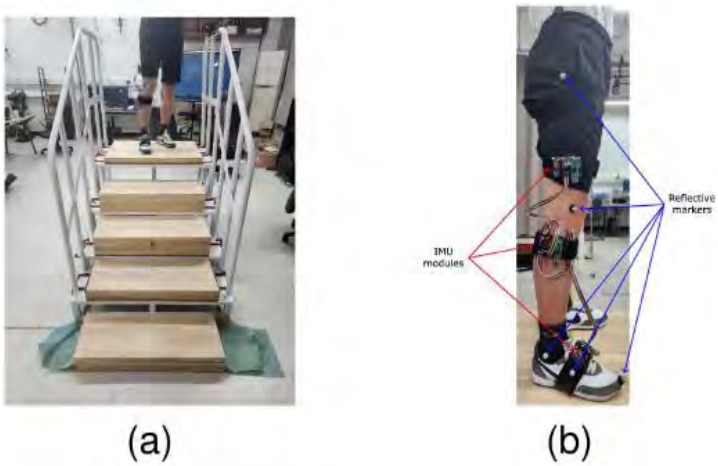

Fig. 4. Experimental device setup. (a) Staircase with four steps, each measuring 185 mm in height, 300 mm in length, and 1 m in width. (b) Reflective markers and IMU modules attached to the right lower limb. Reflective markers are placed on the hip, knee, and ankle joints, side of the foot, and toe, while IMU modules are placed on thigh, shank, and foot.

How NOKOV Contributes to the Research

A stair descent experiment was conducted to validate theproposed phase variable (Fig.4). The staircase, consisting offour steps with a height of 185 mm, a length of 300 mm, and awidth of 1 m, was positioned under nine motion capture cam-eras (NOKOV, 100 Hz). Reflective markers and IMU modules(MPU9250, 100 Hz) were attached to subjects. The marker andIMU data were used to separately obtain the positions of thethigh, knee, ankle, and hip. Additionally, toe-strike and toe-offtimings were detected using the motion capture data.

Citation Cha M, Hur P. Estimation of Gait Phase of Human Stair Descent Walking Based on Phase Variable Approach[J]. IEEE Robotics and Automation Letters, 2025.

Link https://ieeexplore.ieee.org/document/11034712

Full-Perception Robotic Surgery Environment with Anti-Occlusion Global–Local Joint Positioning

Keywords

robotic surgery, global–local joint positioning, data fusion, occlusion avoidance

Abstract

The robotic surgery environment represents a typical scenario of human–robot cooperation. In such a scenario, individuals, robots, and medical devices move relative to each other, leading to unforeseen mutual occlusion. Traditional methods use binocular OTS to focus on the local surgical site, without considering the integrity of the scene, and the work space is also restricted. To address this challenge, we propose the concept of a fully perception robotic surgery environment and build a global–local joint positioning framework. Furthermore, based on data characteristics, an improved Kalman filter method is proposed to improve positioning accuracy. Finally, drawing from the view margin model, we design a method to evaluate positioning accuracy in a dynamic occlusion environment. The experimental results demonstrate that our method yields better positioning results than classical filtering methods.

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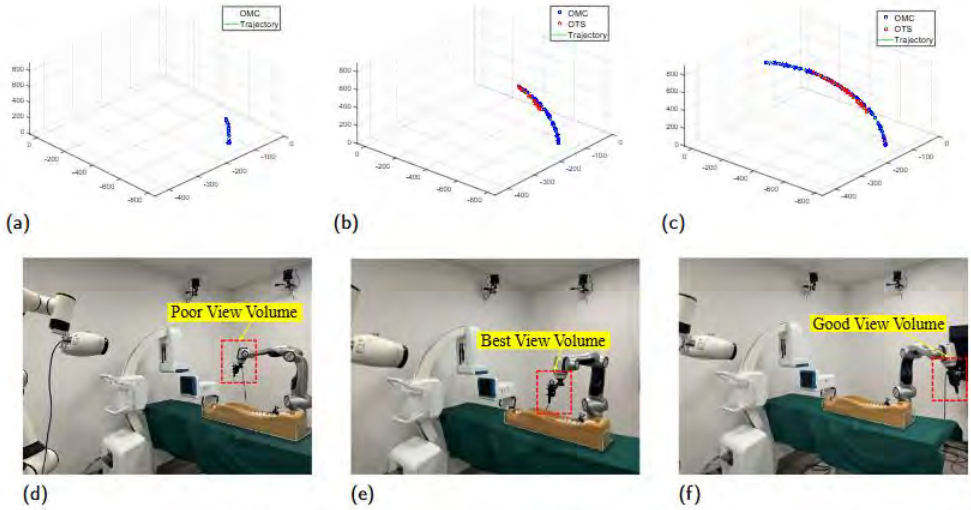

Figure 8. Data collection and actual experimental scenario for Task 4: The robotic arm grasps the target, moves from the PVV to the measurement volume of the OTS (BVV), and then moves out of BVV to reach the GVV; (**a**–**c**) show the collected data and fused results, and (**d**–**f**) demonstrate the actual scene of this process. We can see distortion between OTS and OMC measurement data.

How NOKOV Contributes to the Research

The experimental setup is depicted in Figure 8. We installed an optical motion capture system (model Mars 4H from Nokov) in the simulated operating room to provide global information, and an optical tracking system (model Polaris Vega from NDI) was used to provide local information. An industrial robot arm (model Diana from Agile Robots) served as the gold standard for positioning accuracy. At the outset of the experiment, it is ensured that both positioning systems could see the target and the marker representing the global coordinate system provided by us, ensuring proper initialization of the matrix.

Citation Wang H, Liu T, Chen J, et al. Full-Perception Robotic Surgery Environment with Anti-Occlusion Global–Local Joint Positioning[J]. Sensors, 2023, 23(20): 8637.

Link https://www.mdpi.com/1424-8220/23/20/8637

Gait Prediction for Rehabilitation Robots Based on Deep Learning

Keywords

lower limb rehabilitation exoskeleton robot, gait trajectory prediction model, convolutional neural network, long short-term memory network, attention mechanism

Abstract

Lower limb rehabilitation exoskeleton robots are used for rehabilitation training of patients with lower limb disorders, which can help patients improve their motor ability. This paper proposes a gait prediction model to predict the gait trajectory of the wearer to improve the human-robot cooperation ability of lower limb rehabilitation exoskeleton robots and the wearing experience of patients. The gait trajectory prediction model is constructed based on convolutional neural network (CNN), long short-term memory network (LSTM), and attention mechanism. For training the model, human gait data is collected utilizing the motion capture equipment. In detail, the spatial coordinates of each lower limb joint are used as the input vector, and the angles of hip and knee joints are used as the output and feedback input vectors. Results show that the model achieves excellent performance on predicting the movements of human lower limbs. The model has theoretical significance for improving the motion control and operation performance of exoskeleton robot.

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Fig. 4. Experimental platform

How NOKOV Contributes to the Research

Motion capture systems are capable of tracking and record-ing joint positions, which are widely used in gait research. NOKOV 3D infrared passive optical motion capture system is used in this paper. The system is mainly composed of six opti-cal infrared cameras, reflective markers, and data transmission equipment.

Citation Ren J, Wang A, Ma Z, et al. Gait prediction for rehabilitation robots based on deep learning[C]//2022 International Conference on Advanced Mechatronic Systems (ICAMechS). IEEE, 2022: 86-90.

Link https://ieeexplore.ieee.org/document/10003463

Human Gait Data Augmentation and Trajectory Prediction for Lower-Limb Rehabilitation Robot Control Using GANs and Attention Mechanism

Keywords

gait prediction; attention; lower-limb rehabilitation robot; LSTM

Abstract

To date, several alterations in the gait pattern can be treated through rehabilitative approaches and robot assisted therapy (RAT). Gait data and gait trajectories are essential in specific exoskeleton control strategies. Nevertheless, the scarcity of human gait data due to the high cost of data collection or privacy concerns can hinder the performance of controllers or models. This paper thus first creates a GANs-based (Generative Adversarial Networks) data augmentation method to generate synthetic human gait data while still retaining the dynamics of the real gait data. Then, both the real collected and the synthesized gait data are fed to our constructed two-stage attention model for gait trajectories prediction. The real human gait data are collected with the five healthy subjects recruited from an optical motion capture platform. Experimental results indicate that the created GANs-based data augmentation model can synthesize realistic-looking multi-dimensional human gait data. Also, the two-stage attention model performs better compared with the LSTM model; the attention mechanism shows a higher capacity of learning dependencies between the historical gait data to accurately predict the current values of the hip joint angles and knee joint angles in the gait trajectory. The predicted gait trajectories depending on the historical gait data can be further used for gait trajectory tracking strategies.

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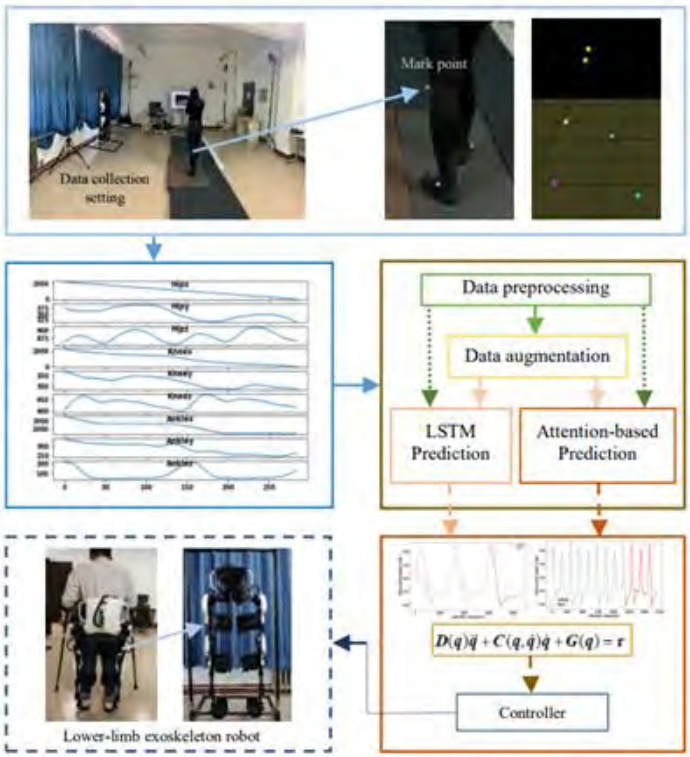

Figure 1. Gait trajectory prediction for lower-limb exoskeleton rehabilitation.

How NOKOV Contributes to the Research

The human gait data in the work are acquired from a NOKOV passive infrared optical motion capture platform [47], referring to the data collection setting in Figure 1. There are six cameras uniformly spaced in two lines along the walls in the lab environment. The data collection associated procedures were approved by Zhongyuan University of Technology Research Ethics Committee (Project identification code ZUTSEI202008-001). All subjects gave their informed consent for inclusion before they participated in the data collection. During the data collection, each participant is instructed to walk at his/her own normal way under the setting of NOKOV. The captured gait data are recorded in the format of three-axis position values from each of the six mark points placed on human body (see Figure 1).

Citation Wang Y, Li Z, Wang X, et al. Human gait data augmentation and trajectory prediction for lower-limb rehabilitation robot control using GANs and attention mechanism[J]. Machines, 2021, 9(12): 367.

Link https://www.mdpi.com/2075-1702/9/12/367

Human Gait Prediction for Lower Limb Rehabilitation Exoskeleton Using Gated Recurrent Units

Keywords

Gait prediction, Gated recurrent units, Lower limb rehabilitation robot

Abstract

Strokes or injuries may cause lower-limb severe movement deficits. These years, lower limb rehabilitation robots show great potential in rehabilitation. In the exoskeleton control strategy, the gait prediction or gait planning becomes a fundamental problem. This paper focuses on the gait prediction using Gated Recurrent Unit Model, working on the raw data captured from an optical motion capture platform by a healthy subject. The designed model learns the history gait data and predicts the current values based on the axis values from the hip and the ankle, without any manual feature engineering. The univariate axis values are processed to a 3D shape to the supervised prediction model. Experimental results show the excellent prediction performance in terms of the error rate of 0.0 or 0.01 on all the 31 trails. The accurately predicted values can be used as the reference trajectories for later rehabilitation. Furthermore, the predicted axis values can be further transformed into the torque values or the angular velocity values used as the actuation input for an exoskeleton robot.

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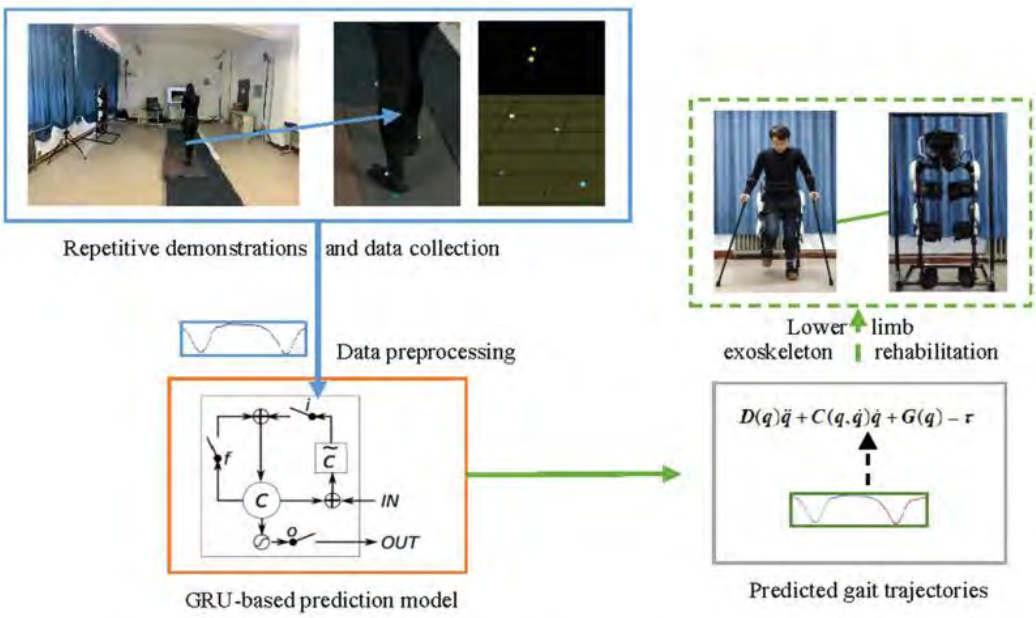

Fig. 1. Gait prediction for lower limb exoskeleton rehabilitation

How NOKOV Contributes to the Research

The study uses NOKOV passive infrared optical motion capture platform collecting the human gait data, referring to Fig. 1, and we have the same camera layout with the work in [6]. The consent had been taken from the subject before data collection. One healthy subject was instructed to walk at self-paced normal walking speeds under the environment of NOKOV. The subject is a female and aged 23, with the thigh length of 47cm, shank length of 40cm, and foot length of 22cm. We finally acquire 31 trials of the gait data from the subject. The average walking duration of all the trials is 3.45s, with the shortest of 2.95s and the longest 4.33s. The gait trajectories were captured in the format of the three-axis values from each of the six markers. The markers were in parallel attached to the hip, the knee, and the ankle of each body side during the data collection.

Citation Wang Y, Li Z, Chen Y, et al. Human gait prediction for lower limb rehabilitation exoskeleton using gated recurrent units[C]//RiTA 2020: proceedings of the 8th international conference on robot intelligence technology and applications. Singapore: Springer

Link https://link.springer.com/chapter/10.1007/978-981-16-4803-8_15

Human Gait Process Analysis and Rehabilitation Robot Humanoid Control Based on OpenSim

Keywords

Human gait, humanoid control, rehabilitation robot, OpenSim, joint moment

Abstract

The existing exoskeleton rehabilitation equipment still has great obstacles to the compliance tracking of normal gait. Therefore, the anthropomorphic compliance control of the rehabilitation exoskeleton robot is still a hot research topic. One of the ways to improve this problem is to import the gait characteristics of human normal motion to achieve human-like tracking and control of the robot. This paper collected normal human gait data and obtained smooth gait data after preprocessing such as filtering and interpolation. Then, combine the collected data with OpenSim to build a musculoskeletal model that matches the subject and analyze the high-fidelity model's joint angle and joint moment. Finally, the joint moment signal with the characteristics of human gait is used as the controller input of the exoskeleton robot, and the exoskeleton robot is simulated, analyzed, and verified. The simulation results prove the scientificity and effectiveness of the method.

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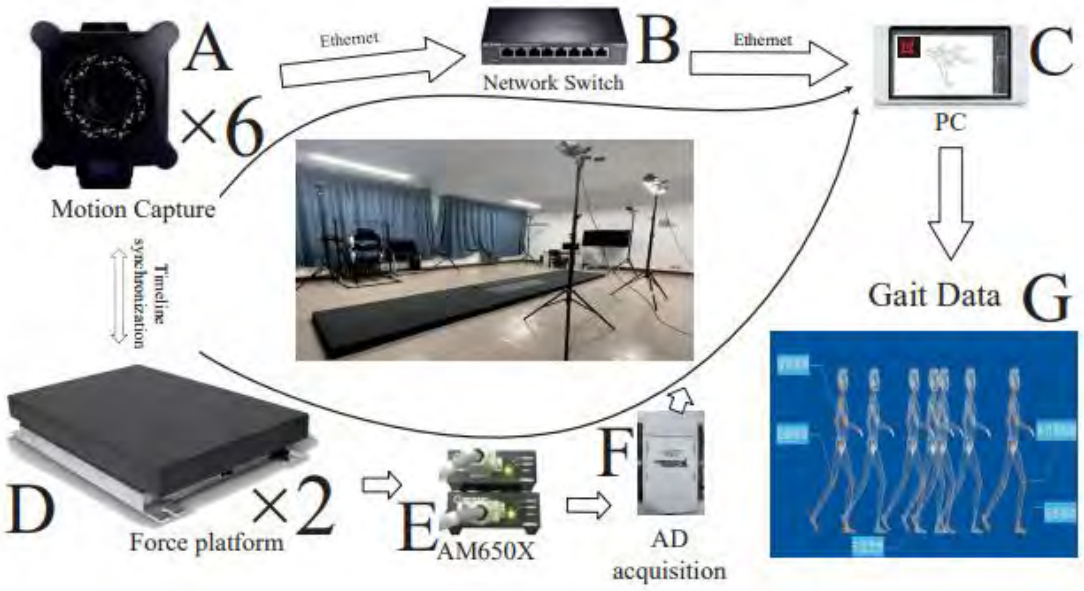

Fig. 1. Gait data acquisition system.

How NOKOV Contributes to the Research

This paper uses the NoKov optical three-dimensional motion capture system to collect human gait data and analyzes the human movement process. Then, the gait data was imported into OpenSim to establishes the kinematics and dynamics model of the joints of the lower limbs, and the gait characteristics of the humanbody are obtained by simulation. The accuracy of the OpenSim model is verified by comparison the gait feature data. The versatility and particularity of the gait feature are obtained at the same time.

Citation Zhang S, Wang A, Ma Z, et al. Human Gait Process Analysis and Rehabilitation Robot Humanoid Control Based on OpenSim[C]//2021 International Conference on Advanced Mechatronic Systems (ICAMechS). IEEE, 2021: 92-96.

Link https://ieeexplore.ieee.org/abstract/document/9661521

Human Lower Limb Motor Ability Estimation Based on Human-Machine Coupling Interactive Contact Model

Keywords

Stroke Rehabilitation · Human-Machine Coupling · Motion Intention Estimation · Dynamic Model · Human-Machine Interaction

Abstract

How to meet the personalized needs of stroke patients in rehabilitation training has long been the core challenge in rehabilitation robot research. The rapid and accurate recognition of patients' motion intentions is a critical prerequisite for addressing this challenge. To address this, this paper presents a method for estimating human lower-limb motor capability based on a human-machine coupling model. Unlike the integrated equivalent model of human-machine coupling, the dynamic models of the mechanical leg and the human lower limb, along with the contact model, are established separately. Identification experiments are then designed to determine the unknown parameters. Then, the mechanical leg and human lower limb are integrated via the contact model to establish a human-machine coupling dynamic model. Based on this model and utilizing torque and interaction force sensors on the mechanical leg, the estimation of human lower-limb motor capability is indirectly realized. Finally, experiments validate the feasibility and effectiveness of the proposed approach.

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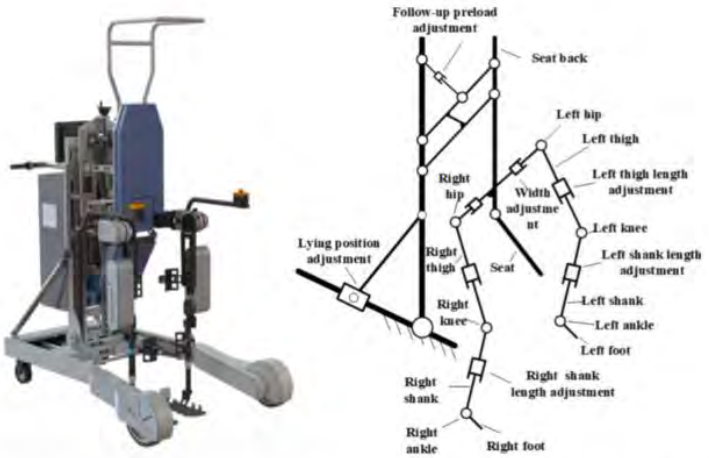

Fig. 1. Degree of freedom configuration of multi-position lower limb rehabilitation robot.

How NOKOV Contributes to the Research

Reflective markers were attached to the subject's lower limbs and the mechanical leg, and the NOKOV motion capture system was used to acquire real-time motion data of the human limbs and exoskeleton. During the experiment, motion data and interaction force data were recorded synchronously, with a total of 10 sets of data collected. After applying smoothing filtering to the collected data, the first 8 sets were selected as the experimental group for parameter identification of the human-machine contact model using a genetic algorithm, while the remaining 2 sets served as the validation group for model verification. The relevant parameter settings are as follows: the initial population size is 1000, the crossover probability is 0.8, the mutation probability is 0.01, the maxi.mum number of iterations is 1000, and the static penalty function is used. The validation group data were input into the model to obtain theoretical torque results. Figure 5 shows the comparison between theoretical calculations and actual measurements for the validation group. The numerical fluctuations in some intervals are caused by the systematic error of the mechanical leg structure, which does not affect the overall result. An overall analysis shows that the interaction force errors for the thigh and calf were generally small, verifying the correctness of the theoretical model.

Citation Gao C, Zhang J, Li H. Human Lower Limb Motor Ability Estimation Based on Human-Machine Coupling Interactive Contact Model[C]//International Conference on Intelligent Robotics and Applications. Singapore: Springer Nature Singapore, 2025: 275-286.

Link
https://ev.publinks.top/app/doc/?docid=cpx_1e62080a19a916fa2f5M7b5210178165218&pageSize=100&index=1&searchId=fe13711a9ed74064be44c28380a6585d&resultsCount=15&usageZone=resultslist&usageOrigin=searchresults&searchType=Quick

Human-Like Control System Design of the Lower Limb Rehabilitation Robot Based on Adaptive RBF Neural Network

Keywords

Human gait data, RBF neural network, Lower limb rehabilitation Robot

Abstract

Lower limb rehabilitation robot (LLRR) brings hope to the patients with lower-limb paralysis. However, the security and stability of the LLRR are still the challenging problems. To provide safer and more effective rehabilitation training for patients, a human-like control system of LLRR based on adaptive radial basis function (ARBF) neural network is proposed. The optical 3D motion capture platform (O3DMCP) is adopted to collect the human gait data (HGD) from the healthy subjects. The HGD is used as the expected trajectory for LLRR, this can make the rehabilitation training more consistent with the human kinematics characteristics. To improve the tracking accuracy, the ARBF neural network controller is adopted estimate the model uncertain parameters. Simulation results demonstrate the effectiveness of the proposed method.

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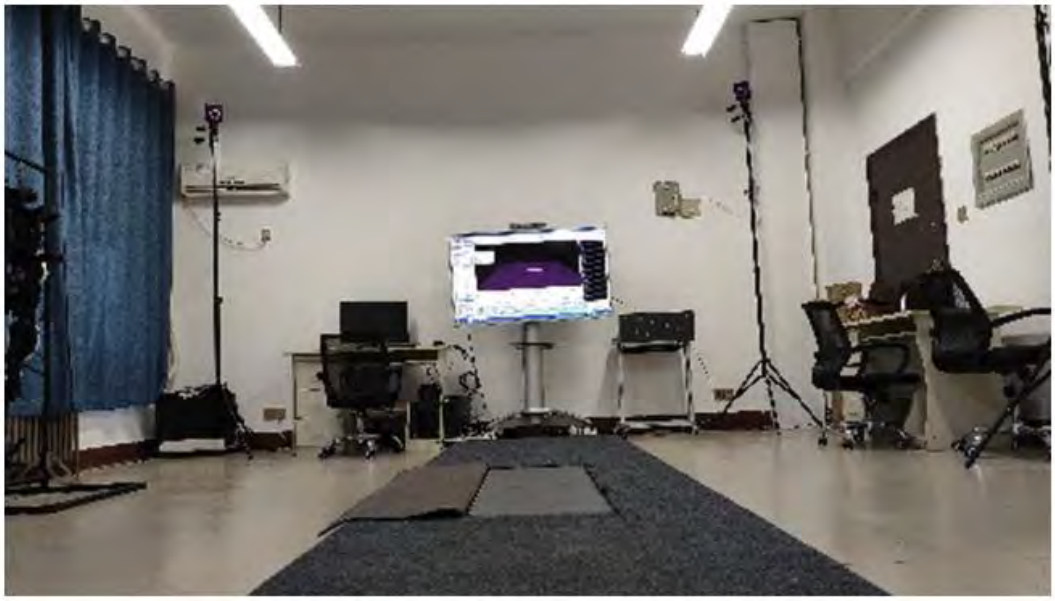

Fig. 1. Motion *capture platform.*

How NOKOV Contributes to the Research

A male subject with 24 years, 80 kg, 180 cm participated in this experiment, and his normal gait trajectory is collected through Nokov O3DMCP [6]. Because of the internal error of the O3DMCP, the waggle of mark points and the influence of some miscellaneous points in the experiment, the obtained trajectory is not smooth enough with some abnormal values. In this paper, the moving average filter is used for smoothing processing, and the 8th order Fourier function is used for curve fitting.

Citation Dan Y, Ge Y, Wang A, et al. Human-Like Control System Design of the Lower Limb Rehabilitation Robot Based on Adaptive RBF Neural Network[C]//RiTA 2020: Proceedings of the 8th International Conference on Robot Intelligence Technology and Applications. Sing

Link https://link.springer.com/chapter/10.1007/978-981-16-4803-8_11

Human-machine Integration of Lower Limb Rehabilitation Robot

Keywords

lower limb rehabilitation robot, rehabilitation training, human gait data acquisition, motor drive control

Abstract

As the prevalence of lower limb motor dysfunction due to conditions such as cerebral palsy, hemiplegia, and paraplegia continues to rise, the current medical infrastructure for sports rehabilitation is insufficient to meet the growing demand. There is also a serious shortage of rehabilitation doctors. In this context, lower limb rehabilitation robots have emerged as a critical role in the rehabilitation process. These robots not only alleviate the workload of rehabilitation doctor but also accelerate patient recovery. Aiming at the shortage in rehabilitation medical resources, this paper introduces a self-developed lower limb rehabilitation robot. This paper encompasses the comprehensive architecture design, hardware development, data collection and processing, control signal transmission, among other aspects. Experimental results demonstrate that the self-developed robot can effectively delivers gait trajectories tailored to the needs of sports rehabilitation, thereby enhancing the efficacy of rehabilitation programs.

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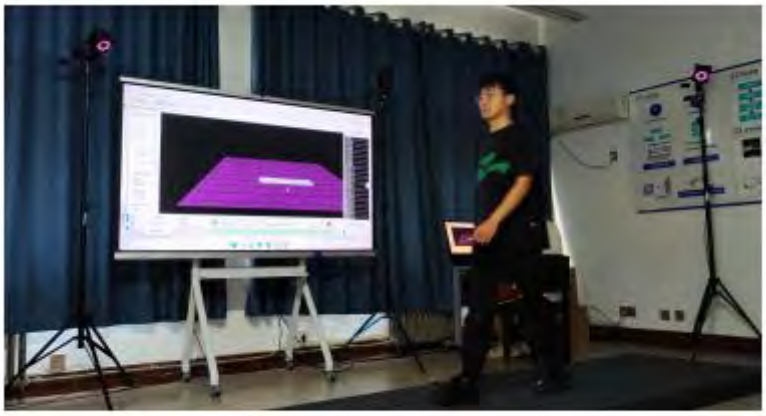

Fig. 3. Data acquisition

How NOKOV Contributes to the Research

The Nokov optical motion capture system used in this paper is device that records the motion of three-dimensional objects, it can be used to collect natural gait from healthy individuals \[16]. The actual measurement scenario we constructed in the laboratory is shown in Figure 3. This experiment measured human gait data by detecting the optical reflection spot attached to the body of the tester with eight cameras. The measured data included the angle changes of hip joint, knee joint and ankle joint, and the force measurement platform was used to simultaneously collect the changes of plantar force.

Citation Zhang X, Wang A, Gao S, et al. Human-machine Integration of Lower Limb Rehabilitation Robot[C]//2024 International Conference on Advanced Mechatronic Systems (ICAMechS). IEEE, 2024: 177-180.

Link https://ieeexplore.ieee.org/document/10818834

Humanoid adaptive sliding mode control based on gait data

Keywords

Lower limb rehabilitation robot; smooth moment output; sliding mode control; gait data; trajectory tracking; adaptive control

Abstract

To address the requirements of lower limb rehabilitation robots for gait trajectory tracking accuracy and output torque smoothness, as well as the need for adaptive identification of the patient's physical parameters. This study proposes a humanoid adaptive sliding mode control approach based on gait data. First, the gait trajectories of healthy individuals are collected using the NOKOV optical motion capture system. Second, the dynamic modeling of the lower limb rehabilitation robot is established through mechanism analysis. Then, a gait feature compensation and inertia compensation method are designed, and the model parameters are adaptively identified to enhance the generalization capability of the lower limb rehabilitation robot for different patients. Meanwhile, sliding mode control is introduced to improve the system ' s disturbance rejection, and an interference prediction method is employed for compensation to suppress the chattering effect of sliding mode control. The stability of the control system is analyzed using Lyapunov's criteria. Finally, the gait trajectories collected from healthy individuals are imported into the simulation system for real gait verification. The experimental results demonstrate that the proposed control method achieves rapid convergence of the trajectory tracking error while effectively suppressing high-frequency and high-amplitude jitter in output torque.

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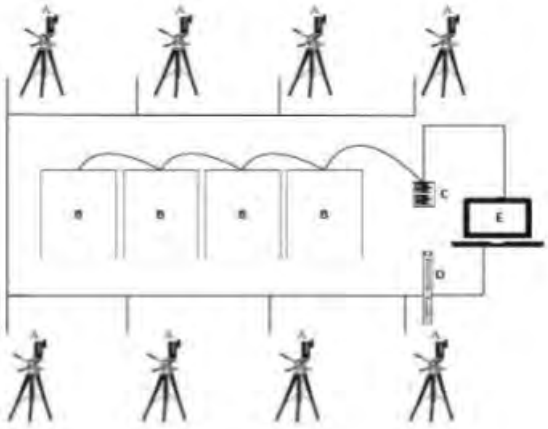

Fig. 1. NOKOV motion capture device

How NOKOV Contributes to the Research

Abstract— To address the requirements of lower limb rehabil-itation robots for gait trajectory tracking accuracy and outputtorque smoothness, as well as the need for adaptive identifica-tion of the patient's physical parameters. This study proposesa humanoid adaptive sliding mode control approach based ongait data. First, the gait trajectories of healthy individuals arecollected using the NOKOV optical motion capture system.Second, the dynamic modeling of the lower limb rehabilitation robot is established through mechanism analysis. Then, a gaitfeature compensation and inertia compensation method aredesigned, and the model parameters are adaptively identifiedto enhance the generalization capability of the lower limbrehabilitation robot for different patients. Meanwhile, slidingmode control is introduced to improve the system's disturbance rejection, and an interference prediction method is employed for compensation to suppress the chattering effect of sliding mode control. The stability of the control system is analyzed using Lyapunov's criteria. Finally, the gait trajectories collected fromhealthy individuals are imported into the simulation system for real gait verification. The experimental results demonstrate that the proposed control method achieves rapid convergence of the trajectory tracking error while effectively suppressing high-frequency and high-amplitude jitter in output torque.Index Terms— Lower limb rehabilitation robot; smooth moment output; sliding mode control; gait data; trajectory tracking; adaptive control.

Citation Wang Y, Wang A, Yue X, et al. Humanoid adaptive sliding mode control based on gait data[C]//2025 IEEE International Conference on Real-time Computing and Robotics (RCAR). IEEE, 2025: 884-889.

Link https://ieeexplore.ieee.org/document/11139437

Hybrid Nursing Robot Based on Humanoid Pick-Up Action: Safe Transfers in Living Environments for Lower Limb Disabilities

Keywords

hybrid nursing robot; humanoid pick-up action; workspace; dynamical model; comfort analysis

Abstract

This research paper outlines the development of a modular and adjustable transfer care robot aimed at enhancing safe and comfortable transfers for individuals with lower limb disabilities. To design this robot, we utilized a 3D motion capture system to analyze the movements of a person assisting another person and to determine the necessary range of motion and workspace for the robot. Based on this analysis, we developed a 3-UPS + UPR parallel spreader to transfer the person receiving care. We also conducted kinematic and dynamic analyses of the parallel spreader to validate its operational space and to obtain the force change curve for the drive. To evaluate the robot's performance, we enlisted the help of ten volunteers with varying heights and weights. Our findings indicate that the pressure distribution during transfers remained largely consistent. Additionally, the surveys revealed that those receiving care perceived the robot as being capable of securely and comfortably transferring individuals between different assistive devices. This modular and adaptable transfer assistance robot presents a promising solution to the challenges encountered in caregiving.

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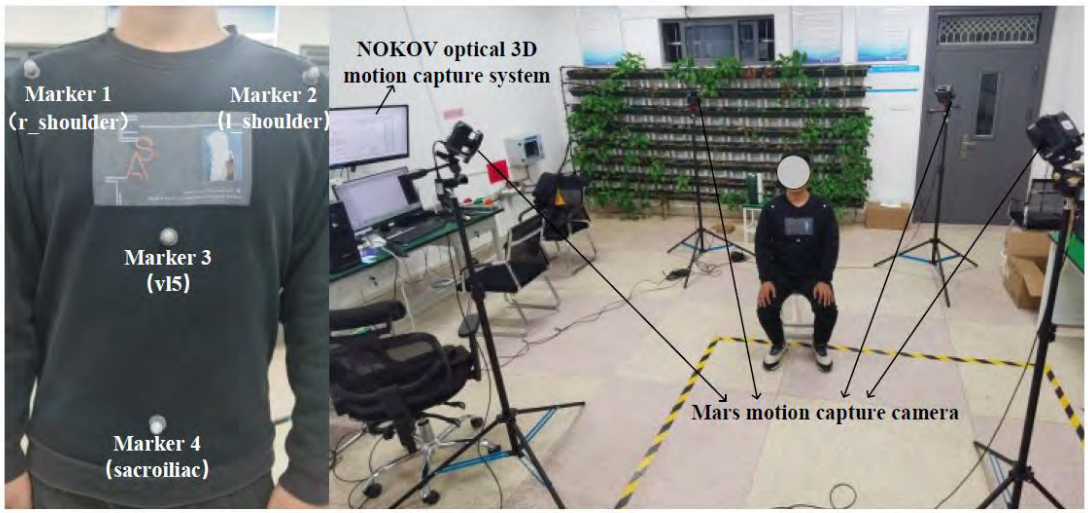

Figure 1. Test arrangement for the pick-up action.

How NOKOV Contributes to the Research

In this test, a NOKOV optical 3D motion capture system was used to capture the actions of the nursed person in the pick-up process [21,22]. According to the standard human skeleton model [23] given in the ISO/IEC19774-Human animation (H-Anim) standard, "r_shoulder", "l_shoulder", "vl5", and "sacroiliac" in the model were selected as the markers (Figure 1). As shown in the figure, a nursed person sat on a chair, nursing person picked up the nursed person and moved them

Citation Li, J.; Wang, C.; Deng, H. Hybrid Nursing Robot Based on Humanoid Pick-Up Action: Safe Transfers in Living Environments for Lower Limb Disabilities. Actuators 2023, 12, 438. https://doi.org/10.3390/act12120438

Link https://www.mdpi.com/2076-0825/12/12/438

Impedance control based on the human gait data for lower limb rehabilitation robot

Keywords

Lower limb rehabilitation robots，impedance controller, gait data, motion capture

Abstract

The lower limb rehabilitation robots (LLRR) have brought significant support to patients with movement disorders, and the research of LLRR has also become one hot topic in robotic fields. However, how to reduce the contact force between the rehabilitation robot and the human is becoming a challenge. Therefore, in order to make robots and humans form a most concerted whole, this paper designs a novel controller based on real human gait data. In detail, the Nokov motion capture system (NMCS) is used to collect human gait data, and then the collected data is fed to the designed control system as reference control signals. That is, the controller can simulate the interaction between the lower limbs of the human body and the environment to provide human-like abilities for the LLRR. To confirm the effectiveness of the proposed method, the simulation results based experimental date is given. The results show a satisfactory trajectory tracking effect, and the stability can be guaranteed.

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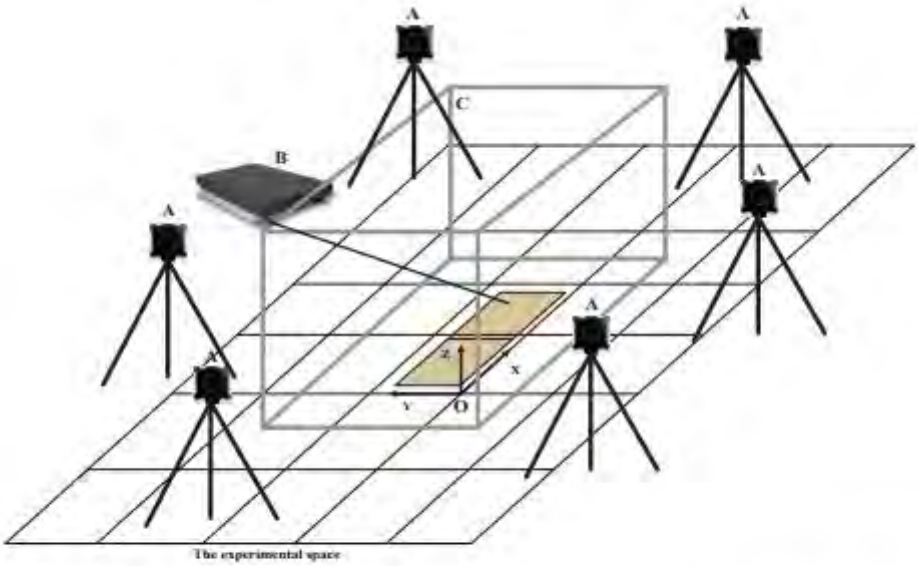

Fig. 1. The experimental space. A: Six infrared cameras. B– 3D force measurement platform. C: The collection space of gait data. O: The origin of the space coordinate after calibration.

How NOKOV Contributes to the Research

Currently, the 3D motion capture system can accurately collect human gait datain the experimental space \[1]. 3D motion capture data can be to identify the geometric parameters and gait trajectory boundaries of the kinematic human lower limb model \[2]. This paper uses theNokovmotion capture system (NMCS) to collect human gait data. The system uses reflective marking points attached to the body surface, then collect the three-dimensional position of the mark on the limbs, which are used to calculate the joints kinematics of the human body.

Citation Wang A, Li W, Yu J, et al. Impedance control based on the human gait data for lower limb rehabilitation robot[C]//2021 China Automation Congress (CAC). IEEE, 2021: 5864-5868.

Link https://ieeexplore.ieee.org/abstract/document/9727345

Individual Gait Generation for Rehabilitation Robots Based on GLS network

Keywords

lower limb rehabilitation robots, long-short term memory networks, sparrow search algorithm, personalized gait generation

Abstract

In recent years, there has been an increase in the number of patients with motor dysfunction due to neurological disorders such as stroke and spinal cord injury. Existing rehabilitation medical resources are unable to provide one-on-one rehabilitation treatment for patients. Lower limb rehabilitation robots (LLRRs) are used as assistants to rehabilitation physicians to help patients with rehabilitation training by simulating the walking gait of a normal person. Each patient's individual degree of impairment varies from person to person, and the parameters of the lower extremity differ, which leads to different rehabilitation training programs used by the patient. Therefore, how to tailor the reference trajectory for patients according to their physical and gait parameters becomes the focus of research at this stage. In this paper, a gait generation model based on GLS network is designed to provide continuous personalized gait trajectories for patients. The GLS network is composed of an LSTM (Long Short-Term Memory) network based on the gap loss function and a sparrow search algorithm (SSA).The gap loss is presented based on the difference between the initial angle and the end joint angle of each cycle. The experimental results are analyzed by mean absolute deviation (MAD). The experimental results show that the gait trajectory generated by the GLS network reduces the experimental error by 16.9 % compared to the trajectory generated by the conventional algorithm (PSO). Therefore, our proposed GLS network-based generation of personalized continuous gait trajectories generates gait trajectories that are more similar to the actual gait trajectories.

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How NOKOV Contributes to the Research

NOKOV motion capture system, composed of 4 force measuringplatforms and 6 cameras. Each camera has a sampling rate of 120 Hz. Thecamera captures the reflective points posted by the subject at the lower limbjoints, records the joint coordinates, and later calculates the joint angle.

Citation Duan H, Wang A, Xin X. Individual Gait Generation for Rehabilitation Robots Based on GLS network[C]//2023 International Conference on Advanced Mechatronic Systems (ICAMechS). IEEE, 2023: 1-4.

Link https://ieeexplore.ieee.org/document/10272901

Individualized Continuous Gait Generation for Rehabilitation Robots Based on LSTM

Keywords

personalized gait generation, long short-term memory networks, lower limb rehabilitation robots

Abstract

The Lower Limb Rehabilitation Robot (LLRR) can provide timely and precise rehabilitation training for patients, but each patient has different body parameters and is in a different rehabilitation period, which means that different training methods have to be used. Therefore, how to develop individualized training methods based on patients' physical and gait parameters has become a major research topic at this stage. In this paper, we choose the Long Short-Term Memory network (LSTM) as a model for gait generation and collect body data and gait data of 23 healthy individuals, with a total of 726 sets of data, to train the LSTM network, and establish the gait generation from input (body parameters. gait parameters) to the output (gait trajectory), and the experimental results were analyzed by mean absolute deviation (MAD), which showed that the trajectories generated by the LSTM network were closer to the actual joint trajectories than those generated by previous methods.

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Fig. 2. Scenarios for gait data collection.

How NOKOV Contributes to the Research

We got a total of 23 volunteers to complete this data collection, the body was measured by ourselves. Figure 1 shows the body parts we want to measure, and Table 1 shows the specific details of the body data. The gait trajectory was collected by the NOKOV optical motion capture system, as shown in Figure 2: it is composed of six infrared cameras (whose maximum frequency is 240Hz) and four force measurement platforms.

Citation Xin X, Wang A, Liao W, et al. Individualized Continuous Gait Generation for Rehabilitation Robots Based on LSTM[C]//2022 International Conference on Advanced Mechatronic Systems (ICAMechS). IEEE, 2022: 1-4.

Link https://ieeexplore.ieee.org/document/10003401

Inverse Dynamic Model using GRU Networks Learning

Keywords

Exoskeleton robot，inverse dynamic model, GRU network, deep learning

Abstract

Considering the designing the controller of a lower limb rehabilitation robot, an accurate inverse dynamic model is usually needed to calculate the joint torque, which is the key to trajectory execution. However, the physical modeling method will have various uncertainties, resulting in inaccurate estimating and measuring physical parameters. Therefore, this paper proposes to use a Gated Recurrent Unit (GRU) to learn the inverse dynamic model. First of all, the gait data and plantar force data of healthy people are obtained synchronously using the NOKOV 3D optical motion capture system and the Bertec 3D force measurement platform. Secondly, using MATLAB, the angle, angular velocity, angular acceleration and joint torque of the hip and knee joints at different moments can be calculated when people walk normally with the data derived from the system. Finally, the calculated joint angles, angular velocities, and angular accelerations are used as inputs to the GRU network, and joint torques are used as outputs to learn the inverse dynamics model of the exoskeleton robot. The evaluation index of the training model is the Root Mean Square Error (RMSE), which eventually settles at about 0.15. The results show that the model has a good learning ability and has made some certain contribution to the development of the exoskeleton robot control system.

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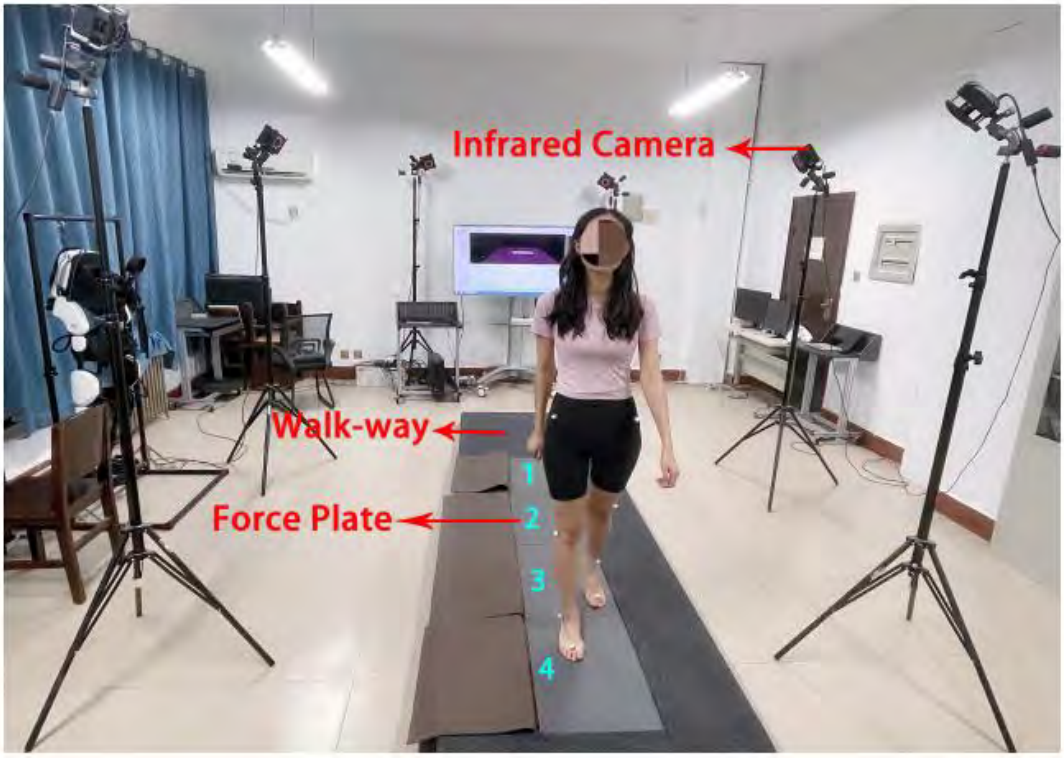

Fig. 6. Data collection scene.

How NOKOV Contributes to the Research

First of all, the gait data and plantar force data of healthy people are obtained synchronously using the NOKOV 3D optical motion capture system and the Bertec 3D force measurement platform.

Citation Song L, Wang A, Ren J. Inverse Dynamic Model using GRU Networks Learning[C]//2021 International Conference on Advanced Mechatronic Systems (ICAMechS). IEEE, 2021: 52-55.

Link https://ieeexplore.ieee.org/abstract/document/9661523

Kinematic-Kinetic Compliant Acetabular Cup Positioning Based on Preoperative Motion Tracking and Musculoskeletal Modeling for Total Hip Arthroplasty

Keywords

SLAM, multi-sensor fusion, UKF, sensor failure

Abstract

The invention of the surgical robot enabled accurate component implantation during total hip arthroplasty (THA). However, a preoperative surgical planning methodology is still lacking to determine the acetabular cup alignment considering the patient-specific hip functions during daily activities such as walking. To simultaneously avoid implant edgeloading and impingement, this study established a kinematic – kinetic compliant (KKC) acetabular cup positioning method based on preoperative gait kinematics measurement and musculoskeletal modeling. Computed tomography images around the hip joint and their biomechanical data during gait, including motion tracking and foot–ground reaction forces, were collected. Using the reconstructed pelvic and femur geometries, the patient-specific hip muscle insertions were located in the lower limb musculoskeletal model via point cloud registration. The designed cup orientation has to be within the patient-specific safe zone to prevent implant impingement, and the optimized value selected based on the time-dependent hip joint reaction force to minimize the risk of edgeloading. As a validation of the proposed musculoskeletal model, the predicted lower limb muscle activations for seven patients were correlated with their surface electromyographic measurements, and the computed hip contact force was also in quantitative agreement with data from the literature. However, the designed cup orientations were not always within the well-known Lewinnek safe zone, highlighting the importance of KKC surgical planning based on patient-specific biomechanical evaluations.

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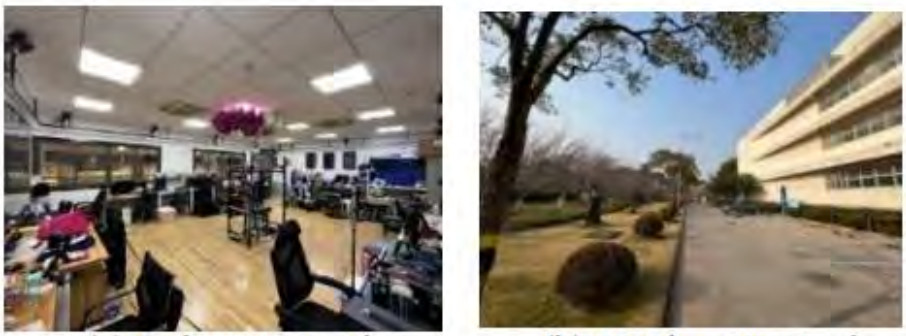

(a) Indoor Scenario (b) Outdoor Scenario

Fig. 2. Experiment scenes.

How NOKOV Contributes to the Research

As shown in Fig. 1, the patient-specific gait data were measured based on a modified Helen Haynes marker arrangement (Burnett et al. 2015, Wang et al. 2022), with 19 reflective markers placed on the following anatomical landmarks: the anterior superior iliac spine, the midpoint of the posterior superior iliac spine, the front side of the thigh, the lateral femoral condyle, the medial femoral condyle, the tibial trochanter, the lateral malleolus of the fibula, the medial malleolus of the tibia, the toe, and the heel. Following a standing-based calibration, participants were asked to walk at a self-selected velocity for three repetitive trials, and motion tracking was synchronously performed by an eight-lens infrared motion tracking system (NOKOV Science & Technology Co. Ltd, Beijing, China) at 200 Hz. Each gait trial was performed on two Kistler force plates (Kistler Instrumente AG, Winterthur, Switzerland). The data were collected at 1000 Hz.

Citation Guo J, Tang H, Li X, et al. Kinematic–kinetic compliant acetabular cup positioning based on preoperative motion tracking and musculoskeletal modeling for total hip arthroplasty[J]. Journal of Biomechanics, 2024, 176: 112332.

Link https://www.sciencedirect.com/science/article/abs/pii/S002192902400410X

Kinematics and dynamics analysis of lower limbs based on human motion data

Keywords

Gait trajectory; Data processing; Kinesiology; Human biomechanics

Abstract

For patients with an aging population and patients suffering from movement disorders, the combination of robotic systems and biomedical engineering principles has brought good news to the majority of patients. The analysis of human gait laws can help better develop and research robotic systems. Therefore, this article is based on the idea of using the gait trajectory of a healthy person as the input reference trajectory of the robot, using NOKOV three-dimensional infrared motion capture equipment and three-dimensional force measurement platform equipment to collect human gait movement data and plantar force data, and analyze the collected data Kinematics and dynamics characteristics of human body data.

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How NOKOV Contributes to the Research

Through the comparison of domestic motion capture systems, this paper adopts theNOKOV3D infrared passive optical motion capture system with better effect. Its system components mainly consist of 6 Mars2H lenses (as shown in Fig.1), connectors, tripods, three-way pan/tilt, connecting wire, calibration rod (T-shaped and L-shaped calibration rods), NK- Cortex software, and reflective markers (Marker).

Citation Hu N, Wang A. Kinematics and dynamics analysis of lower limbs based on human motion data[C]//2020 Chinese Automation Congress (CAC). IEEE, 2020: 6727-6732.

Link https://ieeexplore.ieee.org/abstract/document/9327180

Learning from Demonstration: Dynamical Movement Primitives Based Reusable Suturing Skill Modelling Method

Keywords

Learn from demonstration; Suturing skill; Dynamical movement primitives; Modeling method

Abstract

Establishing a surgical skill model plays an important role for automatic robotic assisted surgery, besides that it is of great value to evaluate physicians' operational skills. In this paper, superficial tissue suture is selected as the modeling object, and suture skill learning and modeling research is conducted. In order to solve the problem of conventional models with poor migration ability for applications in new scenes, a demonstration-decomposition-modeling suture skill learning and modeling framework is proposed. The demonstration suture process is decomposed into sub-processes that repeats in various suture paradigms. The dynamic movement primitives (DMPs) method is introduced to uniformly model the suture trajectory of each sub-process. The superficial suture operation demonstration and acquisition platform is built, and the modeling ability of the proposed method and the adaptability to new scenes are preliminarily verified.

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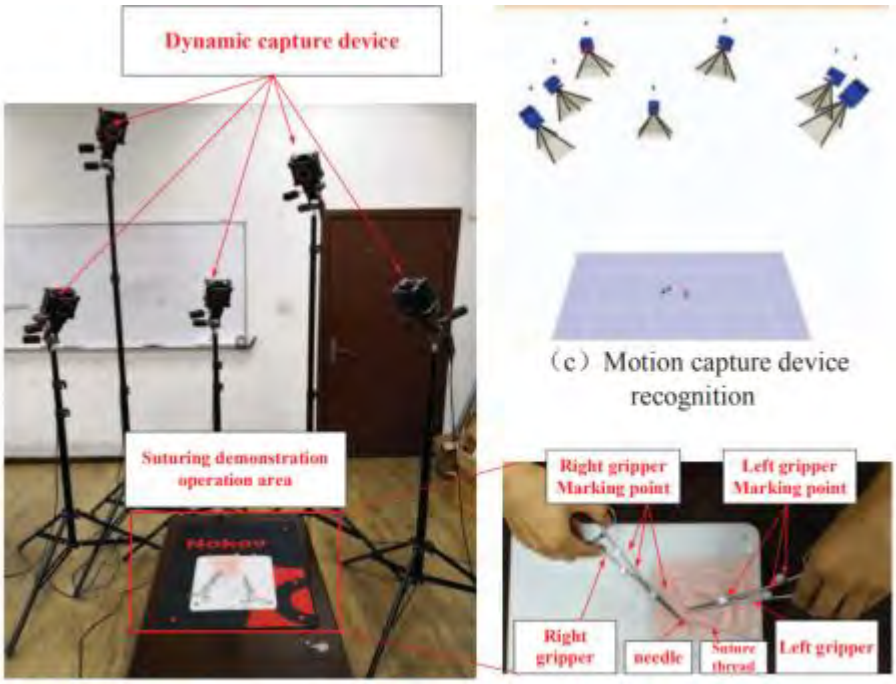

How NOKOV Contributes to the Research

The Nokov optical motion capture system is an optical three-dimensional motion capture system. In this experiment, 7 optical lenses were used to measure and track the suturing process. Six marker points were attached on the two surgical clamps. The 3D position of the marker points on the surgical forceps are collected, and the continuous motion trajectory (namely the spatial position and posture) of the surgical forceps can be calculated and recorded on the Nokov system in real time. By means of coordinate system transformation method, we can analyze the motion trajectory of the surgical forceps in the wound coordinate frame.

Citation Yang D, Lv Q, Liao G, et al. Learning from demonstration: dynamical movement primitives based reusable suturing skill modelling method[C]//2018 Chinese Automation Congress (CAC). IEEE, 2018: 4252-4257.

Link https://ieeexplore.ieee.org/abstract/document/8623781

Lower limb rehabilitation robot control based on human gait data and plantar reaction force

Keywords

Human gait data; Plantar reaction force; Lower limb rehabilitation robot; Motion capture platform

Abstract

In this paper, to improve the safety and availability of rehabilitation training for patients, a control scheme for Lower limb rehabilitation robot (LLRR) based on human gait data and plantar reaction force is proposed. First, the real normal human gait data obtained by motion capture platform (MCP) is fed to the designed control system, and the plantar reaction force is fed to the LLRR after dynamic calculation. Then, a controller based on joint angle and angular velocity tracking error is designed to realize the trajectory tracking. Finally, for a robot simulation model, the effectiveness of the proposed method is confirmed based on the simulation results.

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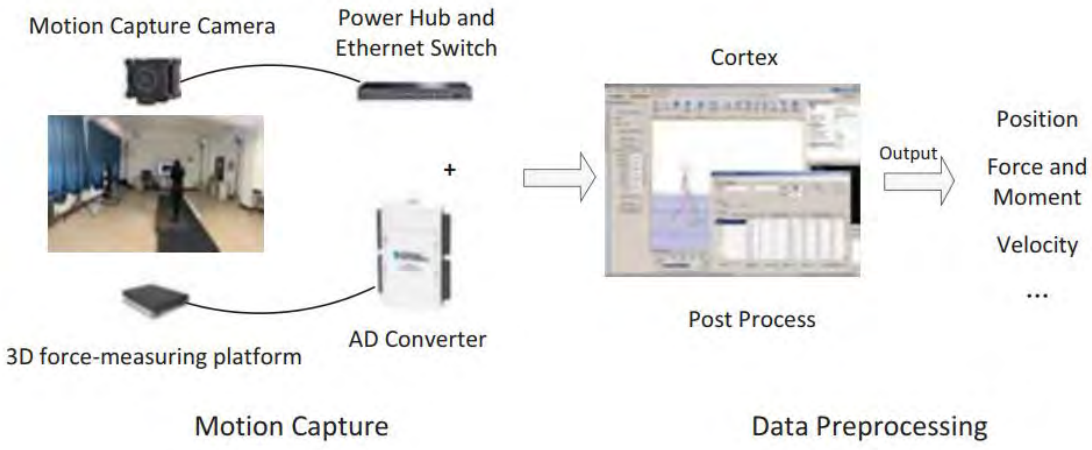

How NOKOV Contributes to the Research

The Nokov OPC equipment adopt the motion capture cameras with ten bits gray-scale depth and GrayScale image processing algorithm, can achieve the precision of millimeter \[16], \[17]. To realize batter control effectiveness, Xu proposed a torque control strategy based on real-time gait event detection \[14], which could control torque and directly drive joint motion based on real-time gait information. However, this control strategy is proposed for the control of a bionic knee exoskeleton. Wang introduced a gait trajectory measurement and planning method \[15]. By measuring and planning the gait trajectory, the ideal controller input of the lower limb rehabilitation robot is obtained, which is used to realize the humanoid movement of the lower limb rehabilitation robot, and improve the safety of rehabilitation training. Wang and Hu proposed a LLRR control system based on human gait comfort \[16], \[17], which can well realize the tracking of human gait trajectory.

Citation Ge Y, Dan Y, Wang A, et al. Lower limb rehabilitation robot control based on human gait data and plantar reaction force[C]//2020 International Conference on Advanced Mechatronic Systems (ICAMechS). IEEE, 2020: 286-289.

Link https://ieeexplore.ieee.org/abstract/document/9310077

Master Manipulator Optimisation for Robot Assisted Minimally Invasive Surgery

Abstract

In robot-assisted minimally invasive surgery, the surgeon controls a robot by operating a pair of master manipulators. Thus, the performance of a master manipulator directly affects the work of the surgeon physiologically and psychologically. In order to improve the operability and quality of operation, a structure optimisation method of master manipulator is proposed. This improves the comfort of the surgeon and can effectively avoid the problem of cutting off master–slave communication to adjust the position of the master manipulator owing to the small workspace.

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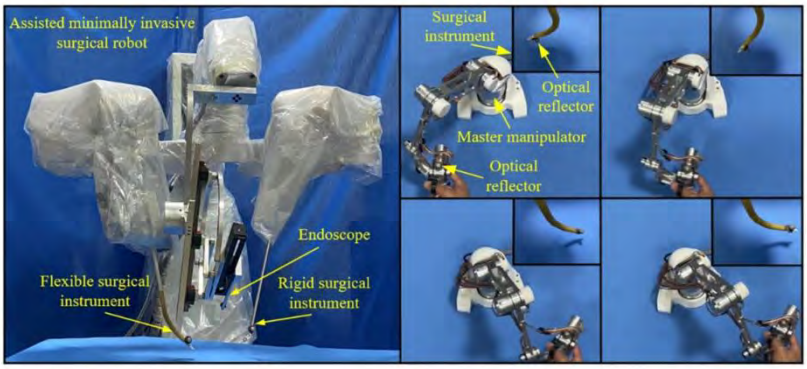

How NOKOV Contributes to the Research

The optimised structural dimensions were used to construct a prototype series-type master manipulator, as shown in Figure 4. To analyse the coverage by the master manipulator workspace of the human hand operation space, surgeons were asked to hold and move the end-effector of the manipulator in the operating posture. An optical reflector was fixed to the end-effector, and the motion capture system of China NOKOV company was used to collect the position of the optical reflector. The envelope of these positions was defined as the workspace. Figure 5 shows the master manipulator workspace and human hand operation space. The master manipulator workspace completely covered the human hand operation space, which can help avoid the problem of cutting off the master–slave communication to adjust the position of the master manipulator.

Citation Feng M, Ni Z X, Li A, et al. Master manipulator optimisation for robot assisted minimally invasive surgery[J]. The International Journal of Medical Robotics and Computer Assisted Surgery, 2021, 17(2): e2208.

Link https://onlinelibrary.wiley.com/doi/abs/10.1002/rcs.2208

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Mechanical Design and Kinematic Modeling of a Cable-Driven Arm Exoskeleton Incorporating Inaccurate Human Limb Anthropomorphic Parameters

Keywords

Cable-driven exoskeleton; Rehabilitation robot; Upper limb

Abstract

Compared with conventional exoskeletons with rigid links, cable-driven upper-limb exoskeletons are light weight and have simple structures. However, cable-driven exoskeletons rely heavily on the human skeletal system for support. Kinematic modeling and control thus becomes very challenging due to inaccurate anthropomorphic parameters and flexible attachments. In this paper, the mechanical design of a cable-driven arm rehabilitation exoskeleton is proposed to accommodate human limbs of different sizes and shapes. A novel arm cuff able to adapt to the contours of human upper limbs is designed. This has given rise to an exoskeleton which reduces the uncertainties caused by instabilities between the exoskeleton and the human arm. A kinematic model of the exoskeleton is further developed by considering the inaccuracies of human-arm skeleton kinematics and attachment errors of the exoskeleton. A parameter identification method is used to improve the accuracy of the kinematic model. The developed kinematic model is finally tested with a primary experiment with an exoskeleton prototype.

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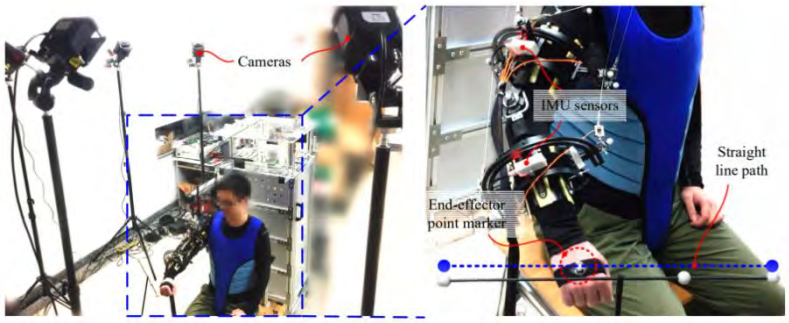

How NOKOV Contributes to the Research

To verify the accuracy of the kinematic models with identified parameters, aNokovmotion capture system was used, as shown in Figure 6. In the motion capture system, a marker was mounted onto the hand of the subjects to measure their tracking results in the experiments. Fourteen markers were mounted onto the cable-routing points of the cuffs to capture changes in the lengths of the cables in the exoskeleton in the tracking task. A marker mounted on the subject' s shoulder joint recorded the movement of the joint center. Noting that as theNokovsystem captures motion with sub-millimeter accuracy, the measurements can be considered as the real results in this work. The captured results can be compared with the identified results to validate the accuracy of the kinematic model.

Citation Chen W, Li Z, Cui X, et al. Mechanical design and kinematic modeling of a cable-driven arm exoskeleton incorporating inaccurate human limb anthropomorphic parameters[J]. Sensors, 2019, 19(20): 4461.

Link https://www.mdpi.com/1424-8220/19/20/4461

Musculoskeletal modeling and humanoid control of robots based on human gait data

Keywords

Human-gait, Musculoskeletal model, OpenSim, Humanoid control, Lower limb rehabilitation exoskeleton, Motion capture

Abstract

The emergence of exoskeleton rehabilitation training has brought good news to patients with limb dysfunction. Rehabilitation robots are used to assist patients with limb rehabilitation training and play an essential role in promoting the patient's sports function with limb disease restoring to daily life. In order to improve the rehabilitation treatment, various studies based on human dynamics and motion mechanisms are still being conducted to create more effective rehabilitation training. In this paper, considering the human biological musculoskeletal dynamics model, a humanoid control of robots based on human gait data collected from normal human gait movements with OpenSim is investigated. First, the establishment of the musculoskeletal model in OpenSim, inverse kinematics, and inverse dynamics are introduced. Second, accurate human-like motion analysis on the three-dimensional motion data obtained in these processes is discussed. Finally, a classic PD control method combined with the characteristics of the human motion mechanism is proposed. The method takes the angle values calculated by the inverse kinematics of the musculoskeletal model as a benchmark, then uses MATLAB to verify the simulation of the lower extremity exoskeleton robot. The simulation results show that the flexibility and followability of the method improves the safety and effectiveness of the lower limb rehabilitation exoskeleton robot for rehabilitation training. The value of this paper is also to provide theoretical and data support for the anthropomorphic control of the rehabilitation exoskeleton robot in the future.

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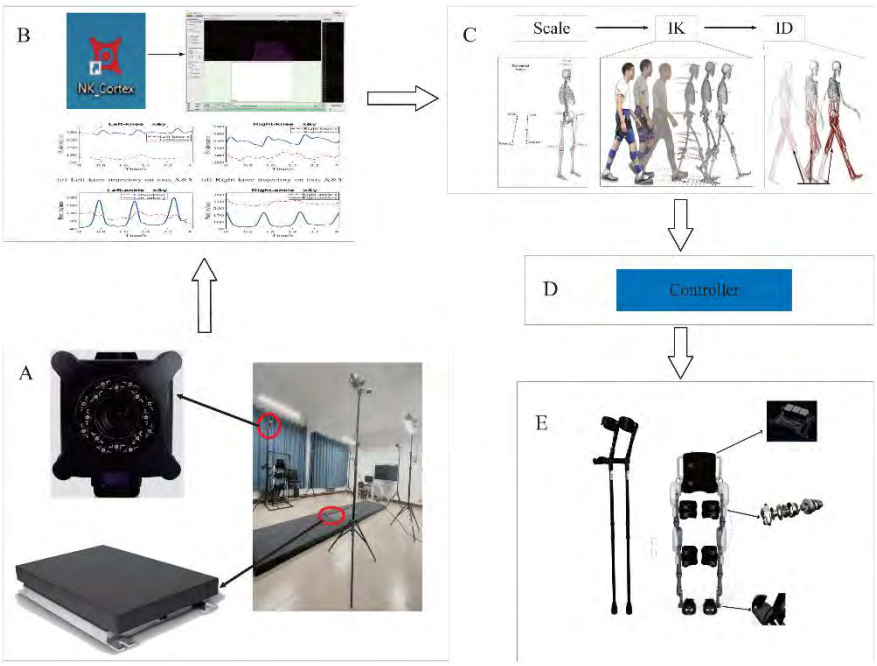

How NOKOV Contributes to the Research

This paper selected Nokov 3D infrared passive optical motion capture system with high accuracy and good effect after comparing several existing motion capture systems and combining with the needs for current research topic. In the scene set up by this system, the infrared camera is used to fully cover the experimental scene, infrared light is emitted by the infrared camera array in the process of data collection, and the position information of the reflective Maker points are captured in the experimental scene. In the process of collecting gait data, the experimental subject walks in the experimental scene with affixed Maker points. In order to meet the needs of the research, the experimental platform is equipped with a three-dimensional force measuring platform, which can synchronously collect the three-dimensional ground reaction force during the movement of the experimental object.

Citation Yu J, Zhang S, Wang A, et al. Musculoskeletal modeling and humanoid control of robots based on human gait data[J]. PeerJ Computer Science, 2021, 7: e657.

Link https://peerj.com/articles/cs-657/

Neural Network-Based Adaptive Sliding Mode Control for Upper Limb Rehabilitation With Disturbance Observer

Keywords

neural network-based adaptive sliding mode controller, nonlinear disturbance observer, robustness, upper limb rehabilitation robot

Abstract

This paper proposes a neural network-based adaptive sliding mode controller combined with a nonlinear disturbance observer to enhance the stability and precision of the upper limb rehabilitation robot in uncertain environments. The upper limb movement intention is initially captured using an optical motion capture system and a surface electromyography acquisition system. An adaptive sliding mode control method, powered by a neural network, dynamically adjusts the controller's parameters to effectively address system uncertainties and external disturbances. The nonlinear disturbance observer in the controller helps identify and mitigate disturbances from the external environment, including Fourier-type, power-type, and mixed disturbances. Furthermore, the stability of the human-machine interaction controller is rigorously verified using the Lyapunov theorem. Simulation results demonstrate that the proposed neural network-based adaptive sliding mode control method significantly improves the performance and robustness of the upper limb rehabilitation robot.

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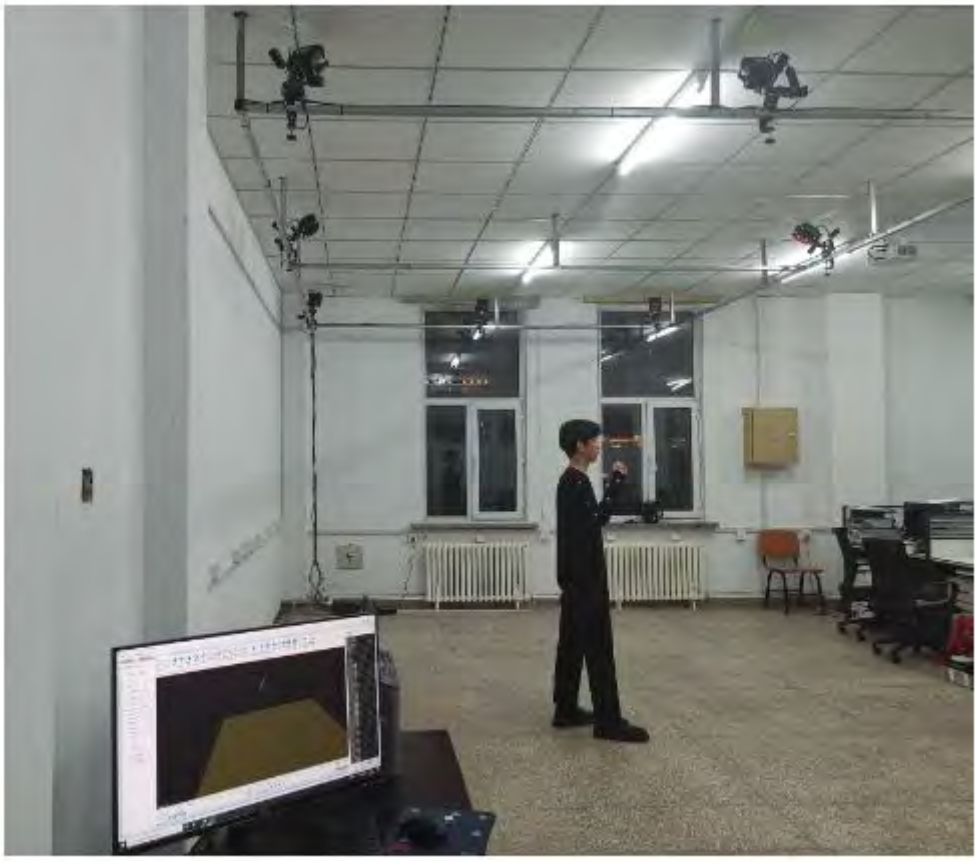

FIGURE 3 | Nokov optical motion capture system.

How NOKOV Contributes to the Research

Figure2shows the specific details of data collection. Biopac sys-tem transmits sEMG data to the host computer through the elec-trode and the wireless acquisition unit . OMC system obtains joint angle data by occupying the positions of the marked points attached to the upper limb, which is shown in Figure3.

Citation Yu C, Li J, Nie B, et al. Neural Network-Based Adaptive Sliding Mode Control for Upper Limb Rehabilitation With Disturbance Observer[J]. Computational Intelligence, 2025, 41(3): e70075.

Link https://onlinelibrary.wiley.com/doi/10.1111/coin.70075

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Noise-tolerant zeroing neural network control for a novel compliant actuator in lower-limb exoskeletons

Keywords

Noise-tolerant zeroing neural network, Compliant actuator, Tracking control, Robustness performances

Abstract

To enhance the safety of direct physical interaction between humans and lower-limb exoskeletons, the actuator of the lower-limb exoskeleton should possess compliance, force controllability, and back-drivability. In this paper, a novel compact compliant force control actuator with worm gear and gear rack as transmission modes is designed to provide flexible power to the lower-limb exoskeleton. The worm gear is utilized to amplify the torque generated by the motor in the compact compliant actuator, while the gear rack is established to improve the bearing capacity. Yet, the friction is occurred between the worm gear, rack and other mechanical configurations which may lead to non-negligible force control error of the compliant actuator. A noise-tolerant zeroing neural network controller is proposed to suppress noises. Additionally, theoretical proofs are provided for the convergence performance of the noise-tolerant zeroing neural network controller, as well as the suppression of constant noise, linear disturbances, and bounded random noise. The proposed noise-tolerant zeroing neural network controller is validated on the compliant actuator through numerical simulations, experimental results, and comparison experiments, demonstrating its effectiveness in suppressing various noise and improving the convergence, stability, and robustness of the compliant actuator system. Additionally, the controller is further verified through walking experiments conducted on a knee robot.

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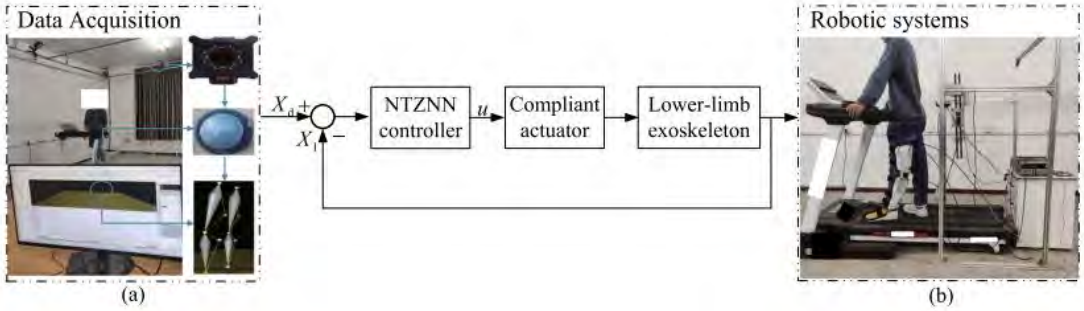

Fig. 10 Lower-limb exoskeleton robot control system. **a** NOKOV optical motion capture system. **b** Walking experiment

How NOKOV Contributes to the Research

The experimental setup depicted in Fig.10a illustrates the acquisition of lower-limb joint angles in healthy subjects using the NOKOV optical motion capture system (Beijing Metrics Technology Co, China). The optical motion apture system is employed for capturing human limb join tangle. The joint angles recorded during the execution of rehabilitation exercises by the subjects serve as task descriptions

Citation Sun Z, Xu C, Wang G, et al. Noise-tolerant zeroing neural network control for a novel compliant actuator in lower-limb exoskeletons[J]. Neural Computing and Applications, 2024, 36(22): 13647-13663.

Link https://link.springer.com/article/10.1007/s00521-024-09789-6

Particle swarm optimization-based unscented Kalman Filter for tremor suppression in minimally invasive surgical robots

Keywords

Minimally invasive surgical robot, Particle swarm optimization, Unscented Kalman filter, Tremor suppression, Signal processing

Abstract

Minimally invasive surgical robots have become extensively utilized in a range of surgical procedures, owing to their precise operation, reduced trauma, and quick recovery times for patients. Despite their effectiveness, physiological tremors in the surgeon's hand may propagate to the robotic arm's end-effector, compromising procedural quality and potentially causing secondary injury. To tackle this issue, a tremor suppression approach was proposed, utilizing the PSOUKF algorithm. First, the simulation model incorporating both surgical and tremor signal characteristics was established, creating a mixed signal that reflected actual operational conditions. The PSOUKF algorithm was then applied to filter the tremor signal, and its suppression effect was compared to alternative algorithms. The experimental findings revealed that the PSOUKF algorithm attained an RMSE of 0.0002, representing reductions of 99.96% compared to the Low-Pass Filter (LPF) and 99.92% compared to the Kalman Filter (KF), respectively. Furthermore, the proposed method achieved a Signal-to-Noise Ratio (SNR) of 63.70 dB, which is approximately 27.7% higher than that of the Unscented Kalman Filter (UKF). The PSOUKF algorithm improved adaptability and robustness by adjusting the noise covariance matrix in complex environments. Additionally, a distributed parallel optimization strategy minimized computational complexity, enabling real-time responsiveness. These findings suggest that the PSOUKF-based tremor suppression strategy can improve the operational accuracy and safety of minimally invasive surgical robots, supporting advancements in robotic-assisted surgery.

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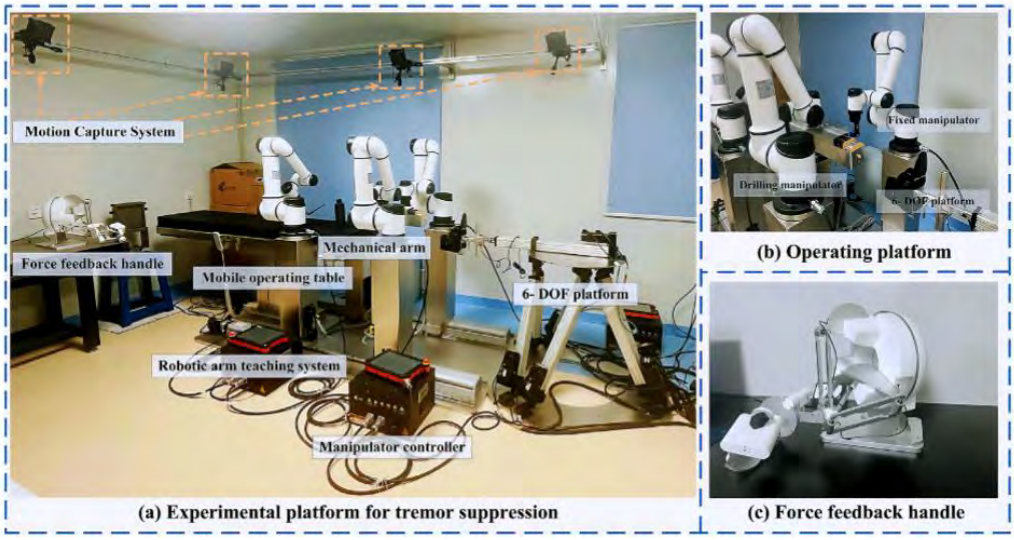

Fig. 14. Tremor suppression experimental platform.

How NOKOV Contributes to the Research

4.1. Construction of the tremor suppression experimental platform
The experimental platform constructed to validate tremor suppression is shown in Fig. 14. To validate the proposed tremor suppression strategy, a master-slave control platform was designed and constructed It integrates hardware and software components to simulate surgical environments, facilitating the evaluation of the PSOUKF algorithm for tremor suppression. The platform includes a master hand force feedback handle, control host, slave robotic arm, and optical 3D motion capture system. These components work together for real-time data acquisition, processing,and system control.
The master hand force-feedback handle is the Sigma.7, a seven-degree-of-freedom device from Force Dimension, with a translation range of 190 x 130 mm and rotation range of 235 x 140 x 200 degrees.It provides a maximum feedback force of 20 N and torque of 400N.m, connected to the control host via USB 2.0 for real-time position data transmission, ensuring precise control and haptic feedback. The slave robotic arm is the AUBO-i5, a six-degree-of-freedom robot (AUBO,Beijing), with a 5 kg load capacity. Its six rotational joints mimic the human arm and communicate with the control system via CAN bus. A teach pendant allows for real-time control and simulation. The optical3D motion capture system, provided by NOKOV, uses Mars 2H cameras(2.2 MP resolution, 0.15 mm tracking accuracy)to track the roboticarm's end-effector position, speed, and acceleration in real time. An NICompact RIO controller and multiple sensor interfaces synchronize data acquisition from the force-feedback handle, robotic arm, and motion capture system for accurate data collection.

Citation Zhou X, Zheng X, Miao G, et al. Particle swarm optimization-based unscented Kalman Filter for tremor suppression in minimally invasive surgical robots[J]. Biomedical Signal Processing and Control, 2025, 110: 108279.

Link https://webofscience.clarivate.cn/wos/alldb/full-record/WOS:001533032400001

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Path Planning for Upper Limb Rehabilitation Based on Human Motion Feature Output

Keywords

upper limb rehabilitation robot, canonical output functions, trajectory optimization, golden section algorithm

Abstract

In the field of rehabilitation robot path planning, the trajectory of rehabilitation training is the premise and foundation of rehabilitation robot control. However, the existing movement trajectory generation methods still have many shortcomings, such as the accuracy of data collection and the effectiveness of optimization algorithms, and rarely consider the laws of rehabilitation medicine. In this paper, the human movement data during the upper limb rehabilitation training is collected through a three-dimensional movement capture system. According to the processed data, find the output of human upper limb movement feature and fit it as an output function to obtain the initial training path of the upper limb rehabilitation training. Adjust the weight of the index to obtain the optimal rehabilitation training path focusing on training effect or comfort by setting the rehabilitation training index. The golden section algorithm is used to calculate the upper limb output data constrained by the rehabilitation training index, and the final human body norm output function is obtained through Fourier fitting. The simulation and results show that the canonical output function improves the efficiency of rehabilitation training and ensures the effectiveness and comfort of upper limb rehabilitation.

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Fig. 1: NOKOV Optical 3D Motion Capture System

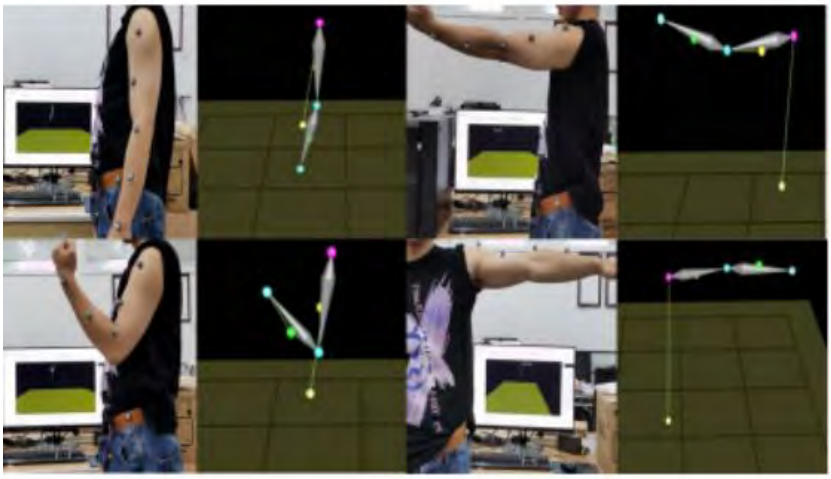

Fig. 2: Experimental posture

How NOKOV Contributes to the Research

The data set in this paper is collected using the NOKOV optical 3D motion capture system, as shown in Figure 1.
The experimental data comes from the NOKOV metrology optical three-dimensional motion capture system.
This is achieved by adjusting the NOKOV measurement software.

Citation Yan Y, He T, Liu Y, et al. Path Planning for Upper Limb Rehabilitation Based on Human Motion Feature Output[C]//2022 IEEE 11th Data Driven Control and Learning Systems Conference (DDCLS). IEEE, 2022: 549-554.

Link https://ieeexplore.ieee.org/abstract/document/9858558

PD Controller of a Lower Limb Exoskeleton Robot Based on Sliding Mode RBF Neural Network

Keywords

LLER, PD, SMRBF-nn, Human gait.

Abstract

The lower limb exoskeleton robot (LLER) is a human-robot interaction device that combines human functions and mechanical characteristics. Due to the complexity and strong coupling of human gait, it is difficult for LLER to be worn comfortably and safely for training. In such a scenario, the paper proposes a kind of proportional-derivative(PD) controller of LLER based on sliding mode RBF neural network(SMRBF-nn). In order to verify the effectiveness of the proposed control scheme, pertinent experiments were carried out. The gait data of the subject was collected through the motion capture system. A simulating model was established, different control methods, like conventional SMRBF-nn controller and PD controller based on SMRBF-nn, have been tested on the LLER. The experimental results show that the control strategy proposed in this paper can not only make LLER track the human body's gait trajectory, but also output appropriate torque when there is a disturbance.

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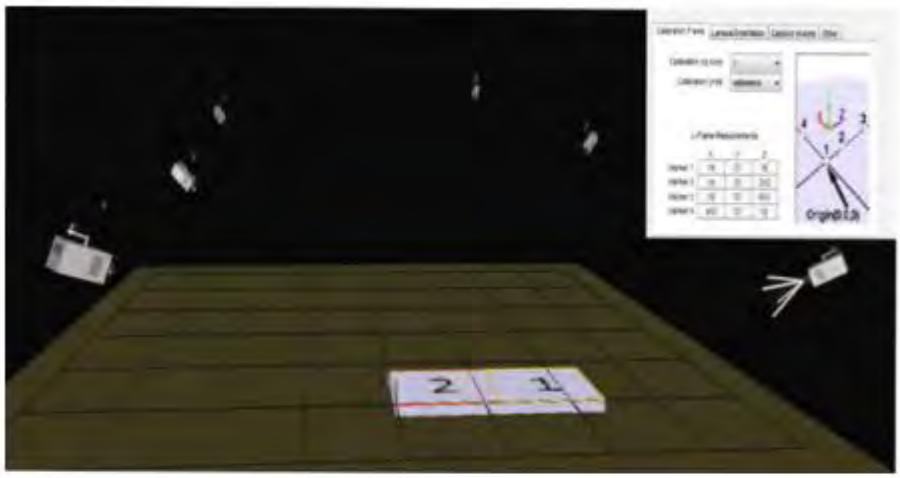

Fig. 2. NoKov optical motion capture system

How NOKOV Contributes to the Research

In this paper, using NoKov optical three-dimensional motion capture system, its gait capture accuracy meets our experimental requirements. This paper employs a control scheme that combines SMRBF-nn with PD to approximate human gait trajectory (as shown Fig. 1). In order to verify the effectiveness of the employed control scheme, we designed a gait capture experiment and MATLAB simulation for normal human. We also compared and evaluated the corresponding simulation results of the employed control scheme.

Citation Wang A, Li W, Yu J. PD Controller of a Lower Limb Exoskeleton Robot Based on Sliding Mode RBF Neural Network[C]//International Conference on Multimedia Technology and Enhanced Learning. Cham: Springer International Publishing, 2021: 427-436.

Link https://link.springer.com/chapter/10.1007/978-3-030-82562-1_40

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Personalized Gait Generation Using Convolutional Neural Network for Lower Limb Rehabilitation Robots

Keywords

lower limb rehabilitation exoskeleton robot, convolutional neural network, personalized gait generation, structural re-parameterization

Abstract

In walking training, tailoring the gait trajectories to accommodate individual patient conditions is pivotal for improving the effectiveness and comfort of rehabilitation. This paper proposes a novel gait generation model based on 1D convolution techniques, capitalizing on the correlation between gait patterns and physiological parameters to learn personalized gait patterns. Firstly, the method applies Fourier fitting to the gait trajectories, incorporating data from hip and knee joints, thereby transforming fitted parameters into a comprehensive representation of the gait trajectory. To improve the network's capability of feature extraction, a multi-branch architecture is utilized, incorporating the squeeze and excitation (SE) blocks to fine-tune the channel weights. Furthermore, the model undergoes structural re-parameterization, a process that converts the multi-branch structure into a single-path structure. This procedure significantly reduces memory usage and computational demand without sacrificing accuracy. Comparative analysis reveals that our model outperforms existing benchmarks, achieving the lowest average loss of 0.1124, thereby demonstrating exceptional generalization capabilities. The optimized model further achieves a 35.63% reduction in inference time, with a negligible average error discrepancy. The generated gait trajectories are intended to serve as reference paths for lower limb rehabilitation robots, thereby offering the groundwork for delivering personalized training to patients.

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Fig. 1. The layout of the experimental scenario.

How NOKOV Contributes to the Research

The gait data, including the spatial coordinates of bilateral hip, knee, and joints, are collected by the Nokov 3D infrared optical motion capture system. As shown in Fig. 1, eight infrared cameras are placed close to the wall, surrounding the measurement area. In the experiment, reflective markers are pasted on the outside of the hip, knee, and ankle joints of volunteers. When volunteers enter the measurement area, the system captures the infrared light reflected by markers and then uses stereo vision technology to calculate the spatial coordinates of these markers.

Citation Ren J, Wang A, Meng L, et al. Personalized Gait Generation Using Convolutional Neural Network for Lower Limb Rehabilitation Robots[C]//2024 IEEE International Conference on Real-time Computing and Robotics (RCAR). IEEE, 2024: 617-622.

Link https://ieeexplore.ieee.org/document/10670989

Physics-Informed Residual Network for Magnetic Dipole Model Correction and High-Accuracy Localization

Abstract

The magnetic dipole model exhibits significant deviations from real-world sensor data due to neglected material nonlinearities and environmental interference. This paper proposed a Physics-Informed Residual Network (PIRNet) that adaptively corrected simulated magnetic field data by integrating dipole theory with deep residual learning. The network took a 5×5 triaxial magnetic matrix as input and employed a dual-branch architecture: a convolutional residual branch extracted local sensor-level distortion features, while a physics-encoding branch models systematic position and orientation-related deviations. A gated fusion mechanism dynamically combined these features, with a divergence-free constraint (\\(\nabla \cdot \mathbf{B} = 0\\)) incorporated as a regularization term. The corrected data was processed through Levenberg-Marquardt (LM) optimization for pose estimation, with subsequent hybrid lookup table compensation combining distance-weighted trilinear interpolation for spatial coordinates and spherical linear interpolation (Slerp) for orientation vectors. Experimental results showed that the positioning error was reduced from 2.1 mm to 1.15 mm, the orientation error was reduced from 3.23° to 1.01°, and the average speed of magnet positioning reached 44.7 ms per frame. This approach provides a high-precision, low-cost sim-to-real transfer solution for magnetic navigation robots.

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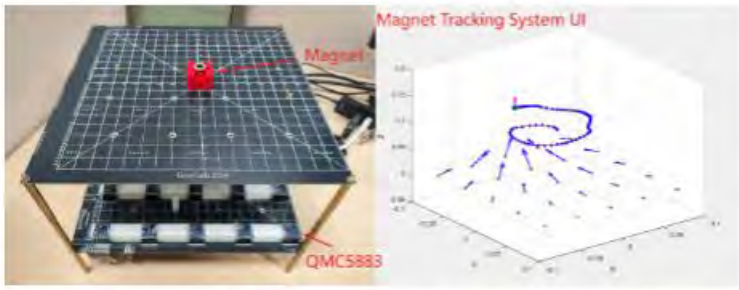

Fig. 3: Experimental platform comprising a magnetometer array (QMC5883), a scale plate, and an annular NdFeB magnet (grade: N45, outer radius $r_o = 10\,\text{mm}$, inner radius $r_i = 5\,\text{mm}$, and length $L = 10\,\text{mm}$). The direction and length of the blue arrow in the UI represents the direction and strength of the magnetic field detected by each sensor.

How NOKOV Contributes to the Research

In this study, as it shows in Fig. 3 a single annular NdFeB magnet was adopted as the magnetic target. As shown in Fig. 3, a self-developed magnetometer array consists of 25 tri-axis magnetometers (QMC5883, QST Corp.) evenly distributed on a 180× 180 mm PCB board. A microcontroller unit (GD32F470ZGT6, GigaDevice) collected the magnetometer data and then transmitted it to a personal computer running Windows 11 with an Intel i7-12700 and a NVIDIA GeForce GTX 1660Ti. To obtain high-accuracy ground-truth data for error evaluation, the magnet's real-time pose was simultaneously recorded by a NOKOV Motion Capture System (Mars 2H), which provided sub-millimeter accuracy.

Citation M. Shen, S. Guo, C. Li and Z. Wang, "Physics-Informed Residual Network for Magnetic Dipole Model Correction and High-Accuracy Localization," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 2171-2

Link https://ieeexplore.ieee.org/document/11246085

Research on robot control system of lower limb rehabilitation robot based on human gait comfort

Abstract

Aiming at the comfort of wearing rehabilitation training robot for patients with lower limb movement disorder, this paper proposes a control method based on real human gait data as the reference trajectory, and designs a control strategy with the comfort of human wearable robot as the objective function, and the wearing rehabilitation training robot can realize the real-time tracking of experimental trajectory of human movement. Firstly, NOKOV motion capture system is used to collect human gait data. Then, the dynamics model of the lower limb rehabilitation training robot's unilateral leg is identified by Lagrange method, and the controller with comfort level as the objective function is designed. The feasibility of the designed control method is proved by Lyapunov stability theorem. Finally, the effectiveness of the proposed method is verified by MATLAB simulation based experimental data on the lower limb rehabilitation training robot prototype.

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How NOKOV Contributes to the Research

Aiming at the comfort of wearing rehabilitation training robot for patients with lower limb movement disorder, this paper proposes a control method based on real human gait data as the reference trajectory, and designs a control strategy with the comfort of human wearable robot as the objective function, and the wearing rehabilitation training robot can realize the real-time tracking of experimental trajectory of human movement. Firstly, NOKOVmotion capture system is used to collect human gait data. Then, the dynamics model of the lower limb rehabilitation training robot's unilateral leg is identified by Lagrange method, and the controller with comfort level as the objective function is designed. The feasibility of the designed control method is proved by Lyapunov stability theorem. Finally, the effectiveness of the proposed method is verified by MATLAB simulation based experimental data on the lower limb rehabilitation training robot prototype.

Citation A. Wang et al., "Research on robot control system of lower limb rehabilitation robot based on human gait comfort," 2019 International Conference on Advanced Mechatronic Systems (ICAMechS), Kusatsu, Japan, 2019, pp. 34-39, doi: 10.1109/ICAMechS.2019.886

Link https://ieeexplore.ieee.org/abstract/document/8861558

Simulation of Limb Rehabilitation Robot Based on OpenSim

Keywords

Lower limb rehabilitation robot; Gait trajectory; OpenSim; Inverse kinematics; Forward dynamics

Abstract

Lower limb rehabilitation robots have been widely used in medical treatment in recent years. The safety of robot in rehabilitation training should be considered. In this paper, the method to analyze complicated inverse kinematics and forward dynamics of lower limb rehabilitation robot is studied. Because of the mathematical model of lower limb is difficult to establish, the OpenSim software is used to simulate and analyze the human gait data which collected by the NOKOV optical motion capture system. According to the inverse kinematics simulation, the curve of each joint angle changing over time is obtained, and the reaction force acting on the ground is obtained through the forward dynamics simulation.

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How NOKOV Contributes to the Research

In this paper, the NOKOV optical motion capture system is used to gain gait data. The cameras which can record each frame marker point movement sequence images are used to real-time motion capture. Because of the limited range of each camera lens, the 6 cameras can be crossed to produce an area. Markers which are captured by two lenses at the same time generate continuous trajectories. Besides, the motion capture system records the spatial coordinates of all markers at the rate of 60 frames per second and its capture accuracy can reach 1 mm. The collected human gait data can be simply processed and exported by the NOKOV system software. In this section, the 6 optical motion capture cameras are arranged in parallel in two columns \[11]. The scene of motion capture and the marking points are shown in Fig. 1.

Citation Wang A, Lu J, Ge Y, et al. Simulation of Limb Rehabilitation Robot Based on OpenSim[C]//International Conference on Bio-Inspired Computing: Theories and Applications. Singapore: Springer Singapore, 2019: 647-654.

Link https://link.springer.com/chapter/10.1007/978-981-15-3415-7_55

Synthesis and Application of Reduced-Dimension Optimization for Rigid-Body Guidance of Stephenson-III Six-Bar Linkages on the Basis of Fourier Harmonic Characteristics

Keywords

Stephenson-III six-bar linkages, rigid-body guidance synthesis, reduced-dimension optimization, Fourier harmonic characteristics, gait rehabilitation, mechanism synthesis and analysis, mechanisms and robots, theoretical and computational kinematics

Abstract

Rigid-body guidance synthesis of linkages must satisfy the requirements of position and posture simultaneously, which increases the difficulty of dimensional synthesis. Extraction of harmonic characteristic parameters via a Fourier series to describe the output motion of the linkage, followed by rigid-body guidance synthesis, is a simple and efficient approach. However, current research on this method has focused mainly on four-bar linkages and simple spherical and spatial mechanisms. There is less research on six-bar linkages, primarily due to the large number of design parameters, the complexity of the motion output, and the difficulty of dimensional synthesis. This article establishes a reduced-dimension optimization synthesis method for rigid-body guidance of the Stephenson-III six-bar linkage on the basis of Fourier harmonic characteristics. The optimization variables do not include the installation dimensions, allowing for the optimization space to be reduced by four dimensions, thereby reducing the optimization complexity. Constraints such as the link length nonnegativity condition, the crank existence condition, the transmission angle condition, and the link length ratio condition are established to ensure the feasibility of the final solution. Finally, on the basis of the task poses at the human ankle joint, a single-degree-of-freedom (DOF) end-traction Stephenson-III six-bar gait rehabilitation training mechanism was synthesized and designed via the proposed rigid-body guidance synthesis method. The trajectory and posture angle curves generated by the prototype experiment were essentially consistent with the theoretical design, verifying the correctness of the theoretical design method and manufacturing assembly as well as the feasibility of the rehabilitation training program.

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Fig. 3 Arrangement of the motion capture system

How NOKOV Contributes to the Research

3.1 Experimental Acquisition and Preprocessing Methods for Human Lower Extremity Movement Data
3.1.1 Experimental Acquisition Equipment, Subjects, and Procedures. The acquisition equipment used was the Nokov optical three-dimensional motion capture system, which is equipped with 12 Mars2H lenses. The arrangement of the motion capture system is shown in Fig. 3.

Citation Yu C, Wang Y, Dai Z, et al. Synthesis and Application of Reduced-Dimension Optimization for Rigid-Body Guidance of Stephenson-III Six-Bar Linkages on the Basis of Fourier Harmonic Characteristics[J]. Journal of Mechanisms and Robotics, 2026, 18(1): 011006

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001654323500007

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Synthesis of a single-degree-of-freedom noncircular pulley-five-bar finger rehabilitation mechanism considering force transfer performance

Keywords

Noncircular pulley-five-bar mechanism, finger rehabilitation, joint force, solution-region synthesis method, optimization

Abstract

Currently, most of the finger rehabilitation mechanisms achieve the desired motion by scale synthesis or using multi-degree-of-freedom (DOF) mechanisms, which cannot simultaneously achieve the requirements of posture and trajectory for finger rehabilitation. Aiming to solve this problem, this study proposes a single-DOF noncircular pulley-five-bar finger rehabilitation mechanism, obtains the pose requirements of finger movement and extracts four important poses. The solution domain of the five-bar mechanism with four poses was solved using the solution-region synthesis method, and the noncircular pulley was used to constrain two rods, making it a single-DOF mechanism. According to the requirements of the finger rehabilitation mechanism and considering the force transmission characteristics of the mechanism, the mechanism parameter optimization model is established, and the optimal parameters are optimized. The calculation model of noncircular pulley transmission is established, and the profile of noncircular pulley is solved according to the obtained rod rotation angle relationship. A finger rehabilitation device was developed, and an experimental study was performed. It was found that the device passed four poses, and the actual trajectory was consistent with the target trajectory. It is confirmed that the single-DOF noncircular pulley-five-bar finger rehabilitation mechanism proposed is effective, and solution method are correct.

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Figure 2. Mark point paste diagram.

Figure 3. Motion capture experiment environment.

How NOKOV Contributes to the Research

In this study, the motion capture experiment is performed by theNOKOVMotion Capture System, which calculates the coordinates, angles, speeds andother kinematic data of the marker points through calculation and analysis. When collecting data using such a system, there are no specific requirements forthe placement of the hand. It is only necessary to accurately attach the markers to the joint points and fingertip points. During the experiment, mark pointsare pasted on the outside of the joint of the human finger, as shown in Figure 2. Subjects perform flexion-extension movements in the Motion Capture Systemvenue. The test environment is shown in Figure 3.

Citation Chen J, Yao K, Yu C, et al. Synthesis of a single-degree-of-freedom noncircular pulley-five-bar finger rehabilitation mechanism considering force transfer performance[J]. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanica

Link https://journals.sagepub.com/doi/10.1177/09544062241271746

Upper-Limb Rehabilitation with a Dual-Mode Individualized Exoskeleton Robot: A Generative-Model-Based Solution

Keywords

Upper-limb rehabilitation, diffusion-based trajectory generation, individualized assistance, compliantly actuated and cable-driven exoskeleton

Abstract

Several upper-limb exoskeleton robots have been developed for stroke rehabilitation, but their rather low level of individualized assistance typically limits their effectiveness and practicability. Individualized assistance involves an upper-limb exoskeleton robot continuously assessing feedback from a stroke patient and then meticulously adjusting interaction forces to suit specific conditions and online changes. This paper describes the development of a new upperlimb exoskeleton robot with a novel online generative capability that allows it to provide individualized assistance to support the rehabilitation training of stroke patients. Specifically, the upper-limb exoskeleton robot exploits generative models to customize the fine and fit trajectory for the patient, as medical conditions, responses, and comfort feedback during training generally differ between patients. This generative capability is integrated into the two working modes of the upper-limb exoskeleton robot: an active mirroring mode for patients who retain motor abilities on one side of the body and a passive following mode for patients who lack motor ability on both sides of the body. In addition, the upperlimb exoskeleton robot has three other attractive features. First, it has six degrees of freedom (DoFs), namely five active DoFs and one passive DoF, to assist the shoulder and the elbow joints and cover the full range of upper-limb movement. Second, most of its active joints are driven by series elastic actuators (SEAs) and a cable mechanism, which absorb energy and have low inertia. These compliantly driven high DoFs provide substantial flexibility and ensure hardware safety but require an effective controller. Thus, based on the singular perturbation approach, a model-based impedance controller is proposed to fully exploit the advantages of the hardware. Third, the safety of the upper-limb exoskeleton robot is guaranteed by its hardware and software. Regarding hardware, its SEAs are tolerant to impacts and have high backdrivability. Regarding software, online trajectory refinement is performed to regulate the assistance provided by the upper-limb exoskeleton robot, and an anomaly detection network is constructed to detect

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and relax physical conflicts between the upper-limb exoskeleton robot and the patient. The performance of the upper-limb exoskeleton robot was illustrated in experiments involving healthy subjects and stroke patient.

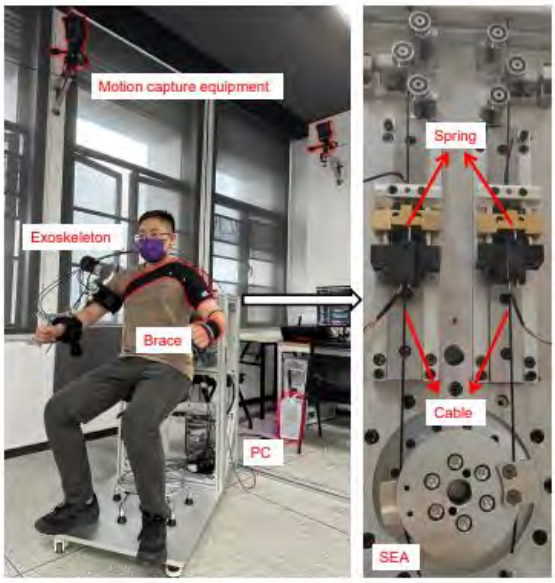

Figure 8. The experimental setup in active mirroring mode used motion capture equipment to obtain feedback from the unaffected side of the body. The SEA was constructed by connecting the motor output and the joint end with a spring and cable.

How NOKOV Contributes to the Research

Figure8 depicts the experimental configuration, in which themain board controlled the impedance of the upper-limb exoskeleton robot. This board was interfaced via a serial port connection with a PC, which was outfitted with an Intel i5-13490F CPU and an RTX 4060Ti graphics card. The PC executed the anomaly detection module,calculated the reference trajectory qr, and dynamically updated the desired trajectory qd online. Subjects performed rehabilitation training in passive following mode or active mirroring mode.In the latter mode, the subject wore a brace equipped with markers on the unaffected side of the body to facilitate engagement in rehabilitation exercises. Optical motion capture equipment (Nokov) was used to accurately capture motion intentions.

Citation Chen Y, Miao S, Ye J, et al. Upper-limb rehabilitation with a dual-mode individualized exoskeleton robot: A generative-model-based solution[J]. The International Journal of Robotics Research, 2025: 02783649251333479.

Link https://arxiv.org/abs/2409.03193

A humanoid control strategy based on deep reinforcement learning for enhanced comfort in lower limb rehabilitation robots

Keywords

Lower limb rehabilitation robot, Humanoid control, Deep reinforcement learning, Human gait data

Abstract

The development of humanoid intelligent controllers represents a breakthrough in enhancing the effectiveness and comfort of rehabilitation training using lower limb rehabilitation robots for diverse gait patterns. In this study, a kinematic model of the lower limb rehabilitation robot is established based on a simplified link structure. For dynamic modeling, the Lagrange formulation is employed to analyze human lower limb motion from an energy-based perspective. Gait data were collected from five healthy subjects, with each performing 20 walking trials, yielding a total of 100 gait cycles for analysis. The acquired gait data are filtered and fitted to plan a reference trajectory of anthropomorphic joint angles suitable for rehabilitation training. Joint torques are computed from plantar force data and the dynamic model, serving as feedback for the controller and used in comfort assessment. A humanoid control strategy integrating Deep Reinforcement Learning (DRL) and a Proportional-Differential (PD) controller is proposed. This approach facilitates individualized gait trajectory planning for rehabilitation training by learning human gait characteristics. Simulation results demonstrate that the proposed method not only improves the intelligence and human-likeness of the robot but also significantly enhances comfort during training.

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Fig. 7. The lower limb rehabilitation robot.

How NOKOV Contributes to the Research

The Nokov motion capture system was used for gait data collection. Reflective markers were placed on key anatomical landmarks of the subject according to a conventional gait model. The subject walked at a self-selected comfortable speed on a level walkway. The motion capture system synchronized with a floor-embedded 3D force plate to record ground reaction forces simultaneously. The scenario is illustrated in Fig. 6.

Citation Jin Y, Zhang J, Li W, et al. A humanoid control strategy based on deep reinforcement learning for enhanced comfort in lower limb rehabilitation robots[J]. Scientific Reports, 2026.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001696989300005

A Physics-Informed Residual Learning Methodfor Real-Time 5-DoF Magnetic Localizationin Capsule Endoscopy

Keywords

Anti-interference integration, ex vivo validation, magnetic capsule endoscopy, physics-informed neural network, sim-to-real

Abstract

Real-time localization is a requirement for the clinical application of magnetically actuated wireless capsule endoscopy. This study proposes a physics-informed deep learning framework to address the model-plant mismatch inherent in analytical methods and the data requirements of end-to-end learning. A dual-branch residual network, physics-informed residual network, computes corrections for the magnetic dipole model. Two operational paradigms are evaluated: a lookup-table-based approach and an end-to-end optimization approach. Experiments indicate that the framework achieves a mean position error of 0.69 +/- 0.29 mm and a mean orientation error of 0.70 +/- 0.37(degrees), utilizing less than 20% of the calibration configurations required by data-driven baselines. Validation includes an ex vivo signal propagation study through biological tissue and compatibility tests with an anti-interference filter, supplemented by a preliminary in vivo animal experiment. The results provide a methodology for sim-to-real transfer in robotic capsule tracking systems.

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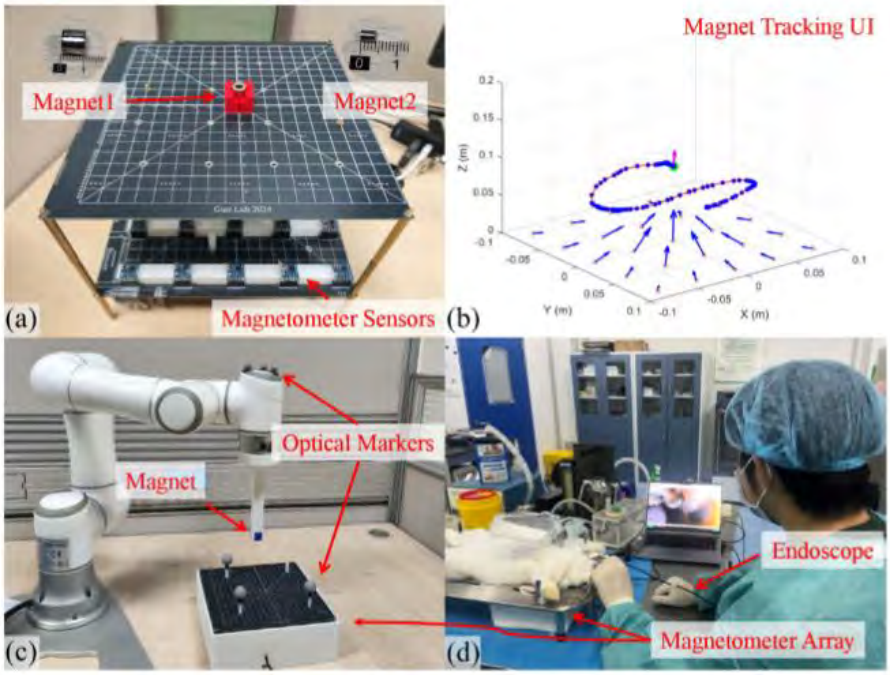

Fig. 3. Experimental platforms. (a) Magnetometer sensor array and magnetic targets. (b) Magnetic tracking user interface, where blue arrows indicate the measured magnetic field vectors. (c) In vitro experimental setup with the optical ground-truth system. (d) In vivo animal study overview.

How NOKOV Contributes to the Research

2)Ground-Truth Acquisition: For in vitro and ex vivo tests, a Mars 2H multicamera optical NOKOV motion capture system provides the baseline 6-degree-of-freedom pose data with a certified accuracy of ±0.15 mm at 380 frames per second. An Elite Robots EC63 collaborative arm executes predefined trajectories. For the in-vivo animal study, optical tracking is structurally obstructed; therefore, the endoscopic video feed and calibrated insertion depth markers are strictly utilized to assess macroscopic trajectory consistency.

Citation Shen M, Guo S, Wang Z, et al. A Physics-Informed Residual Learning Method for Real-Time 5-DoF Magnetic Localization in Capsule Endoscopy[J]. IEEE Transactions on Industrial Informatics, 2026.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001767458000001

Structural Design and Performance Analysis of a Deep-Learning-Based Adaptive Variable-Stiffness Lower-Limb Rehabilitation Exoskeleton

Keywords

Variable stiffness; Self-powered system; Deep learning; Health monitoring Personalized rehabilitation; Embodied intelligence

Abstract

With the continuous advancement of global rehabilitation technologies, home-based lower-limb rehabilitation exoskeletons have demonstrated broad application prospects due to their low cost and high convenience. However, significant inter-patient variability, the complex and dynamic nature of the rehabilitation process, and the time-varying characteristics of knee joint torque present major challenges for these exoskeletons in accurately matching torque demands during training. Designing scientifically-grounded, personalized rehabilitation programs and precisely regulating training intensity in home settings remains a highly complex and challenging task. To address this challenge, we propose a home-use knee health monitoring system (KHMS) grounded in embodied intelligence, featuring three key innovations: (i) a four-bar variable-stiffness mechanism that provides adjustable stiffness over 10–40 N·m/rad; (ii) a self-powered electromagnetic module that delivers a stable 3.4 V output to reliably energize low-power wireless sensors; and (iii) an LSTM-based adaptive monitoring model that estimates knee joint torque with 95.36% accuracy and supports continuous rehabilitation-state tracking. By enabling real-time assessment and data-driven personalization based on individual recovery trajectories, the proposed KHMS facilitates scientifically grounded home training with precise intensity regulation. Overall, this work advances practical, portable rehabilitation devices that can meet community-level rehabilitation needs and promote the development of low-power artificial intelligence.

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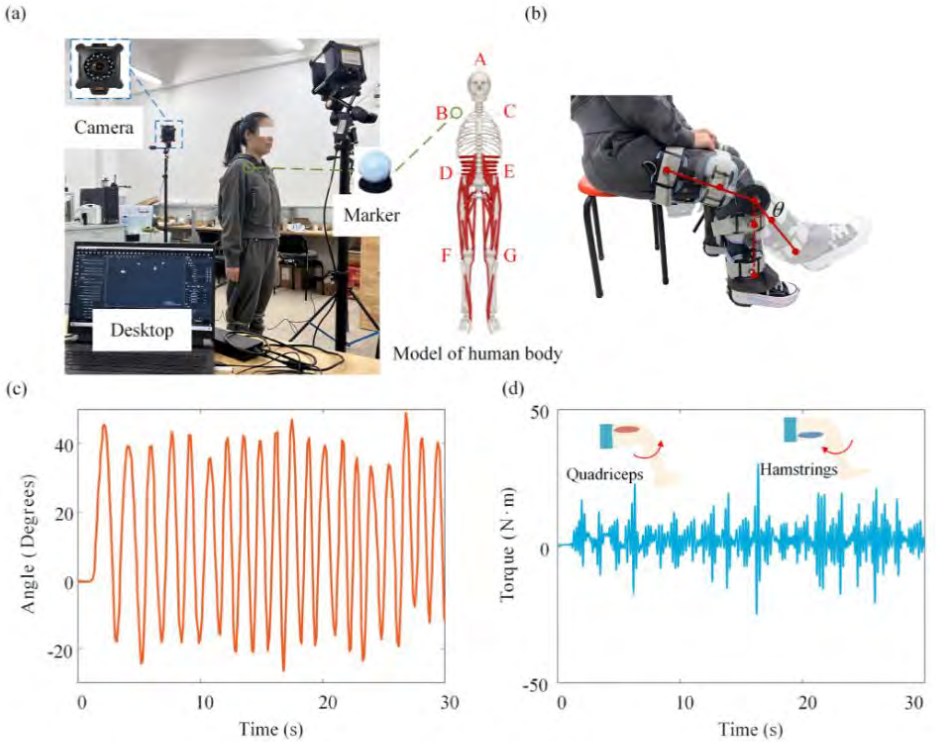

Fig. 8 Human knee joint torque data acquisition: **a** schematic diagram of the experimental setup for human model construction; **b** schematic diagram of leg swing angle acquisition; **c** angle vs. time curve; **d** torque vs. time curve

How NOKOV Contributes to the Research

In this study, a three-dimensional motion capture and analysis system NOKOV (Fig. 8a) was employed to record key anatomical landmarks of the participants, including the shoulder, hip, and the medial and lateral markers of both knees. The collected marker data were used to scale the human model in OpenSim, enabling the simulated model to better fit the individual characteristics of each participant. During the simulation, the joint angle (Fig. 8c) and torque variation (Fig. 8d) of the participant's knee during swinging were recorded and collected for subsequent analysis. The collected data were trained and analyzed via a deep learning model to obtain the knee joint torque information.

Citation Wang Y, Wang C, Wang Z, et al. Structural design and performance analysis of a deep-learning-based adaptive variable-stiffness lower-limb rehabilitation exoskeleton[J]. Acta Mechanica Solida Sinica, 2026: 1-15.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001698074000001

动力型 TKA 术后辅助康复装置设计及应用研究

关键词

KOA 人群；辅助康复；结构设计；PLC 控制系统；

摘要

随着社会老龄化加剧,膝关节骨性关节炎(Knee osteoarthritis,KOA)人群逐年增加,且发病趋于年轻化。由于疾病的不可逆性,大多患者最终会选择全膝关节置换术(Total knee arthroplasty,TKA)进行治疗,然而术后康复中存在的不当训练易导致慢性疼痛和心理抑郁等问题,对患者的正常生活产生严重影响。针对上述问题,本文提出了一种动力型 TKA 术后辅助康复装置,患者可在卧姿状态下完成主、被动两种训练模式。主要研究内容包括:(1)膝关节生物力学分析与康复机构设计。通过对人体膝关节的运动生物力学分析,对 KOA 的损伤机制进行了剖析,分析患者进行膝关节置换术后的身体状态,确定了患者术后不同时期的康复训练需求；同时,确定了实现四个术后常见康复动作所需的机构,并进行几何运算与运动仿真,确定了主、被动训练的相关康复参数。(2)TKA 术后辅助康复装置设计。借助几何分析所得出的相关康复参数,进行了电动推杆、传感器等部件选型及装置的整体结构规划；依据康复训练策略,将装置整体分为被动关节灵活度训练和主动肌力训练两个部分,细化了实现各康复动作的装置结构；同时,借助 Solidworks 三维建模软件实现了方案的初步展现。(3)TKA 术后辅助康复装置控制设计。考虑动作实现方式和装置控制要求,完成了 PLC 和人机界面的选型与控制硬件电路设计；借助台达 WPLSoft 软件实现通讯和驱动控制指令的编写,并用 DOPSoft 软件实现人机界面的编写,两者配合实现了康复模式、康复参数的选择和康复训练状态的实时监控。(4)TKA 术后辅助康复装置性能分析。利用 Solidworks 进行关键受力部件静力学分析,并简化模型导入 ADAMS 中进行了实际状态的运动仿真；构建实物样机,使用 NOKOV 动作捕捉系统和传感器测试了使用过程中的髋、膝关节角度及足底压力,利用 MATLAB 计算了各关节力矩数据,将实验测试与数值模拟结果进行了对比,并分析了误差产生的原因；同时,制定舒适度评价量表,完成了装置的舒适度评价。

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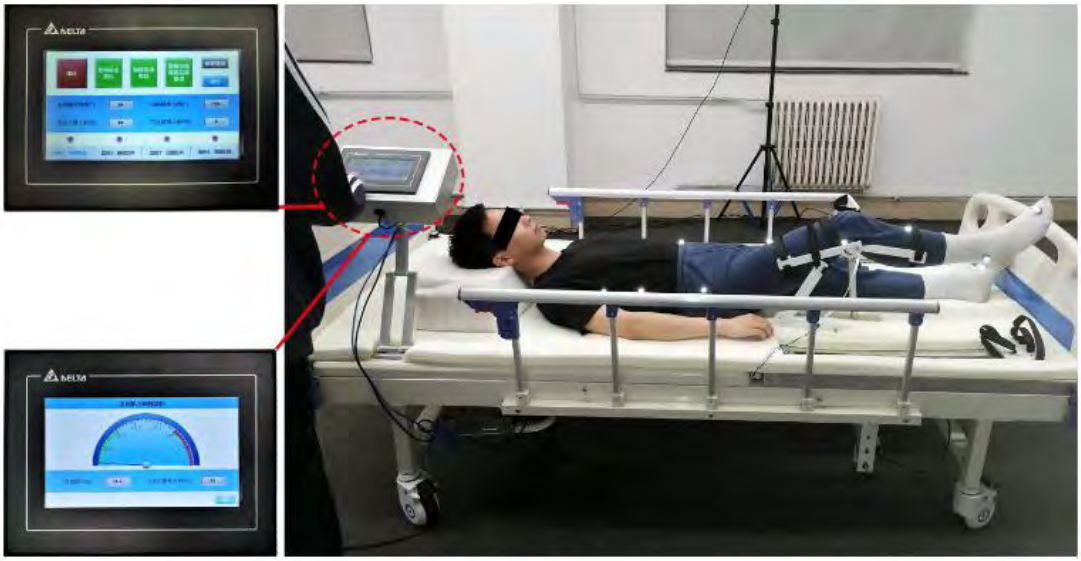

图 5-21 训练数据采集

NOKOV 度量动作捕捉在研究中的应用摘录

在康复装置实物加工完成的基础上，借助 NOKOV 动作捕捉系统采集志愿者康复训练中的下肢数据，与正常人对应数据进行对比，完成装置的客观评价。
此次实验所使用的 NOKOV 三维动作捕捉系统由摄像头、MARK 标记点、L 型标定杆、T 型标定杆和软件系统组成。摄像头包括 8 台 Mars 系列动作捕捉相机，使用三脚架固定，其分辨率最高可达 1200 万像素，频率最高可达 300HZ，镜头采用十位灰阶深度+GrayScale 图像处理算法的双优组合，云计算，多镜头并联，使 Nokov 光学动作捕捉系统可以进行更精确、更迅速、更稳定的实时运动捕捉，实现亚毫米级的捕捉精度；MARK 标记点为带有发光小球的传感器，便于摄像头的捕捉；L 型与 T 型标定杆用于摄像头的标定；软件系统则使用 Seeker 软件进行操作，Seeker 为一款运动分析软件，支持系统标定、校正、数据采集、导出等操作，可以借助系统中多个镜头实时处理，得到标记点的三维坐标和每个镜头在空间的位置信息。

引用格式 刘刊. 动力型 TKA 术后辅助康复装置设计及应用研究[D]. 西安理工大学,2023.DOI:10.27398/d.cnki.gxalu.2023.001239.

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GAN 和注意力机制用于步态数据增强和轨迹预测

关键词

数据增强；轨迹预测；生成对抗网络；注意力机制；步态康复；

摘要

近年来,随着人口老龄化的加剧,由中风或者受伤导致下肢运动障碍的人越来越多。利用下肢外骨骼辅助康复训练可以帮助行动不便的人重新获得行走能力,具有很高的应用价值。特定的外骨骼控制跟踪策略往往需要大量的步态数据和步态轨迹数据用于设计和训练。数据收集的高成本或隐私等问题导致人体步态数据非常稀缺,这将影响控制器或模型的性能。本研究提出了基于生成对抗网络（GAN）的数据增强方法,以生成大量合成的步态数据,减轻数据采集的负担。同时提出基于注意力机制的步态轨迹预测模型,用于对真实和合成的步态数据进行步态轨迹预测,提高预测精度,为外骨骼跟踪控制器提供及时的步态轨迹数据。实验结果表明:本研究所构建的数据增强模型能够合成逼真的多维人体步态数据；注意力预测模型能够更好地学习历史步态数据之间的依赖能力,准确地预测步态轨迹中关节角度的当前值。主要研究内容有:

（1）通过运动捕捉系统获取真实的人体步态数据,考虑在采集过程中由于环境和设备的影响导致的数据缺失等问题,对原始数据进行预处理来获得有效的原始步态数据。

（2）针对大量人体步态数据难以获取的问题,本研究提出一种基于生成对抗网络的人体步态数据增强模型。该模型同时优化重组损失、对抗损失、监督损失和无监督损失来考虑多维数据之间的相关性,以合成仿真的人体步态数据并保留原始步态数据的动态特性。我们采用多种相似度度量方法对合成数据进行验证。实验结果表明提出的步态数据增强模型可以合成与原始步态数据相似的多维人体步态数据。

（3）为了给下肢康复机器人控制跟踪策略提供及时的步态轨迹值,构建两种步态轨迹预测模型:LSTM 预测模型和注意力机制预测模型。真实步态数据和合成的步态数据输入到构建的预测模型中对步态轨迹进行预测。实验结果表明基于注意力机制的预测模型具有较强的特征表达能力,表现出比 LSTM 模型更高的预测性能。

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图 2.2 步态数据采集场景

NOKOV 度量动作捕捉在研究中的应用摘录

数据采集前首先要做好相关准备，把所要用到的动作捕捉系统布置在一个特定的区域。本研究的采集地点是在一个宽敞的实验室里面，房间容量足够支持设备的摆放，在该实验室中，我们把主要的显示屏放在实验室中间，为了可以更好的观察步态数据采集情况，同时把 6 个相机放在实验室的两侧，通过镜头来捕捉人体行走时的步态位置坐标信息。数据采集如下图 22 所示。本实验用到的硬件设备和软件设备包括红外动作捕捉镜头、Nokov 动作捕捉软件、反光标识点、POE 交换机和若干标定框和镜头固定装置组成。其本质是定位系统，通过计算分析得到相关的角度、加速度等运动学数据。

引用格式 李志康.GAN 和注意力机制用于步态数据增强和轨迹预测[D].中原工学院，2022.DOI：10.27774/d.cnki.gzygx.2022.000268.

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基于表面肌电信号的人体手臂关节运动信息预估及人机顺应协作研究

关键词

表面肌电信号；运动意图识别；人机交互；机器学习

摘要

随着社会的不断发展，机器人被期望走进人类生活之中，为人类提供更多、更好的服务。但是传统机器人缺乏对外界环境的感知和顺应能力，因此很难安全地与人类进行带有物理接触的交互行为。提高人机交互效果的关键在于，选择合适的传感器捕捉人体的运动信息，再从中分析和提取出人类的运动意图，并将其反馈到机器人控制程序中。通过这种方法，机器人根据人类的运动意图调整自己的行为模式，从而做到对人类运动的顺应。表面肌电信号中蕴含了丰富的人体运动信息，而且其采集设备具有无创、易穿戴的优点，适合用于人机交互。因此，本文基于表面肌电信号，建立了人体手臂的动作类别、关节角度、速度和力矩的预估模型，并建立了对应的人机顺应协作框架。本文的主要研究内容包括：

首先，本文设计了基于阈值迭代的线性判别分类器(LDA)。分类器能够从表面肌电信号中对做连续运动的人手进行动作分类。在设定的人机交互实验中分类器获得了 89% 的识别正确率。进一步地，本文建立了基于小波变换和反向传播神经网络(BPNN)的拟合模型。模型能够从表面肌电信号中拟合出人手肘关节的角度和速度信息。为了验证模型的拟合能力，本文在不同运动条件下进行了实验。实验结果表面，预估关节角度的均方根误差为 0.15rad；预估关节速度的均方根误差为 0.21rad/s，这说明模型能够有效地预估关节的角度和速度。

然后，本文对关节力矩信息的预估方法展开了研究。为了提高关节力矩信息的预估准确度，本文引入了视觉捕捉系统，搭建了基于表面肌电信号-视觉(s EMG-Vision)的力矩预估模型。模型混合了自编码器和 BPNN，实现从表面肌电信号和视觉系统中预估人手肩、肘关节的力矩信息。通过实验来评价关节力矩预估模型的性能。实验结果表明，模型在拟合肩、肘关节力矩的均方根误差分别为 2.43N.m 和 0.34N.m。相比于不引入视觉捕捉系统的预估模型，均方根误差分别下降了 25% 和 55%，表现更加稳定。

最后，本文建立了基于肘关节力矩信息反馈的人机顺应协作框架。通过将力矩预估模型预估得到的肘关节力矩信息，反馈到机器人的控制程序中使机器人能够感知人手的运动状态，并以此调整自己的对外输出的力值，从而做到对人手的顺应。本文在 UR5 机器人上测试了所提出方法的有效性。实验结果表明，加入肘关节力矩信息反馈，能够有效提高机器人的顺应性。

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图 3-4 动作捕捉系统摄像头布置图

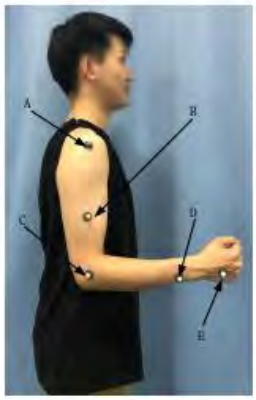

图 3-5. 马克点在人手上的放置图

NOKOV 度量动作捕捉在研究中的应用摘录

3.2.2 基于视觉系统的人手运动信息提取
本文使用了一套视觉系统（ NokovMars1.3H）捕捉上臂的运动，接着从中提取出肩关节和肘关节的运动信息。这套视觉系统由八台红外线高速摄像机组成，能够以 100Hz 的频率提供马克点在世界坐标系中的三维位置信息（如图 3-4）。为了能够计算出关节的信息，将人手的上臂简化成为图 3-1 中的两杆模型。然后在手臂上贴五个马克点 A，B，C，D，E。其中 A 贴在上臂肩关节处，B 贴在连杆 L1 质心处，C 贴在肘关节处，D 贴在连杆 L2 质心处，E 贴在人手末端（如图 3-5），对于两连杆的质心位置如何计算确定，将在下一节中进行介绍。另外再增加带有四个马克点的 L 型杆，放在地面上，作为运动分析的参考坐标系。

引用格式 陈锴彬.基于表面肌电信号的人体手臂关节运动信息预估及人机顺应协作研究[D].华南理工大学，2020.DOI：10.27151/d.cnki.ghnlu.2020.003965.

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基于步态数据的机器人鲁棒自适应 PD 控制

关键词

下肢外骨骼机器人；鲁棒自适应 PD；动作捕捉系统；步态数据；轨迹跟踪

摘要

针对因脑率中等中枢神经系统疾病而导致运动障碍的患者，在康复训练初期，应用下肢康复机器人提供被动康复训练过程中的控制问题，提出了一种基于健康人体步态数据的下肢外骨路机器人的鲁棒自适应 PD 控制。在误差扰动有界的情况下，设计鲁棒自适应 PD 控制策略，不仅能够使下肢外骨骼机器人快速跟踪通过动作捕捉系统获得的人体步态轨迹，并且能够避免初始输出力矩过大。通过 MATLAB 仿真验证了在保证全局稳定的情况下，所提方法具有良好的跟踪性能和抗干扰能力。最后，通过角度相似度函数客观评价在所提控制方法下人体运动的舒适性。

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图 1 动作捕捉系统及 mark 点位置

Fig. 1 Motion capture system and mark location

NOKOV 度量动作捕捉在研究中的应用摘录

目前主流的人体步态采集设备中，光学运动捕捉是首选，因为它可以高精度地测量附着在一些相关的身体地标上的小反射标记。所以本文采用 NOKOV 三维红外被动光学动作捕捉系统采集到的人体运动步态数据，将其滤波拟合后作为外骨骼机器人控制器的数据输入，然后提出一种基于真实的人体步态数据的鲁棒自适应 PD 控制策略，不仅能够很好地进行步态轨迹跟踪，而且对下肢康复机器人系统的结构参数进行了在线辨识，同时避免了初始力矩过大的问题。最后通过仿真实验验证所提方法的可行性和有效性，在运动过程中通过机器人的步态轨迹与人体步态轨迹的相似性对人体的舒适性进行客观评价。

本文所用动作捕捉系统为 NOKOV 三维红外被动式光学动作捕捉系统，其硬件设备主要由 6 个光学摄像机、mark 点、定位杆、校正杆、数据传输设备、上位机等组成。摄像机左右各 3 个分两行排列，首先通过 L 型标定杆、工型标定杆进行空间标定，标定的空间大小取决于人体贴点运动的空间范围， 并调节适当的采样频率，然后在人体的关节处贴上 mark 点，人体在动作捕捉系统的空间内运动时，当关节处的 mark 点能够同时被两台摄像机捕捉到时即可记录下此刻 mark 点的位置信息，动作捕捉系统的捕捉精度可达 1mm，通过采集到的 mark 点的空间坐标信息实时上传到 Cortex 软件，然后通过该软件对采集到的轨迹进行平滑处理，并保存为需要的数据格式。动作捕捉系统及人体关节处 mark 点的位置，如图 1 所示。

引用格式 王瑗珲，胡宁宁，喻俊等.基于步态数据的机器人鲁棒自适应 PD 控制[J].控制工程，2021,28（09）：1738-1746.DOI：10.14107/j.cnki.kzgc.20190609.

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基于步态数据的建模分析与机器人仿人控制

关键词

下肢康复训练；外骨骼机器人；人体肌肉骨骼建模；OpenSim；拟人控制；

摘要

神经性疾病、肢体损伤和老龄化人群的脑卒中均会导致人类下肢运动功能障碍,严重影响了个人生活质量。康复医学的相关研究表明,有效训练可促进肢体功能障碍患者运动功能恢复或重建。然而,现有的被动式康复训练机器人与人体下肢正常运动的契合度不够,康复医师手动训练治疗需要占用大量社会资源,因此,研究"人在回路中"的外骨骼康复训练机器人具有重要的经济和社会意义。本文立足于下肢康复训练机器人,从正常人的人体步态数据出发,结合人体运动的生物力学分析与模型构建,获取具有人体运动特性的关节角度与力矩,并将该信号作为下肢外骨骼机器人模型控制的参考信号,设计控制器实现机器人的拟人化柔顺控制。通过与现有几种人体建模方法和外骨骼机器人建模控制方法的对比分析,本文所提方法在机器人的跟随性与人机融合性方面具有一定的优越性,并通过实验验证了本文所提出的下肢外骨骼机器人拟人建模及控制方法的科学性和有效性。本文主要研究内容包括:

（1）分析、对比了多连杆模型和肌肉骨骼模型两种人体下肢运动学建模理论,通过标识点和光学系统采集步态数据,使用 Open Sim 进行下肢肌肉骨骼建模分析与仿真,再通过逆运动学解算得到人体运动过程中变化的下肢关节角度,并对人体运动机理和步态过程进行了分析。

（2）分析、对比了多连杆模型、人与机器人复合模型和机器人多体运动学三种机器人建模方法,根据采集的运动过程足底交互力进行逆动力学解算得到人体运动过程中下肢的各关节力矩,并与 Open Sim 肌肉骨骼模型逆动力学解算得到的关节力矩进行了对比分析。

（3）研究、讨论了基于真实步态数据的下肢外骨骼机器人拟人建模及控制系统设计方法。即在力矩控制中,将含有人体运动特性的关节力矩作为机器人模型的输入补偿量,从而将人体运动特性引入到控制系统中。以人体运动特性的关节角度与关节力矩作为机器人的参考输入信号,结合建立的机器人模型进行 PD 控制器设计,并仿真验证了该方法的可行性。本文的控制算法分别对连杆机器人模型和多体运动学机器人模型进行了仿真测试,下肢连杆模型实现了髋、膝和踝关节在矢状面上的关节驱动与控制,多体运动学模型实现了与人体相同的多自由度下肢关节驱动控制。

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图 4-2 动作捕捉采集场景

NOKOV 度量动作捕捉在研究中的应用摘录

本文比较了几种现有的运动捕捉系统后，结合当前研究需要，选择了精度高、效果好的 Nokov 三维红外被动光学捕捉系统。在本系统搭建的场景中，利用红外摄像机对实验场景全覆盖，红外摄像机阵列在数据采集过程中发出红外光，通过捕获实验场景中反射 Maker 点的位置信息实现数据采集。在步态数据采集中，实验对象在实验场景中贴上标记点行走，为了满足动力学研究的需要，在实验平台上设置了三维测力平台，可以同步采集实验对象运动过程中的三维地面反作用力。

实验数据动作捕捉采集场景如图 4-2 所示。NoKov 的红外光学相机基于被动式红外光学原理，有 1200 万像素的高分辨率和最高 300 帧每秒的高捕捉率，在运动捕捉领域处于世界领先地位，可以达到亚毫米级的捕捉精度。该装置是基于红外光学检测的，实验只能在没有阳光的房间进行。在实验过程中，窗帘被关闭，以隔离外界的红外干扰。该实验用于采集正常人行走过程中的真实步态数据。

引用格式 张帅帅.基于步态数据的建模分析与机器人仿人控制[D].中原工学院，2022.DOI：10.27774/d.cnki.gzygx.2022.000218.

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基于步态数据的下肢康复机器人控制设计

关键词

步态数据；RBF 神经网络；下肢康复机器人；三维动作捕捉系统；前馈控制

摘要

为了使下肢康复机器人的辅助康复训练更加符合人体运动特性，为下肢运动功能障碍的患者提供更加安全、有效的康复训练，提出一种基于人体步态数据和径向基函数(RBF)神经网络的下肢康复机器人控制策略。首先，以三维动作捕捉系统获取的健康人体步态数据为系统的期望输入；其次，通过 RBF 神经网络自适应控制器产生驱动机器人关节运动的力矩，使机器人的运动轨迹跟踪期望轨迹；然后，采用基于前馈控制的校正模型对机器人的输入力矩进行补偿校正，达到实时校正的目的，从而实现更好的跟踪效果；最后，通过基于实验数据的仿真结果，验证了该方法的可行性和有效性。

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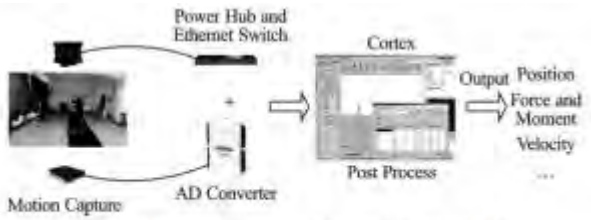

图 2 Nokov 光学三维动作捕捉系统结构图

Fig. 2 Structure of Nokov optical 3D motion capture system

NOKOV 度量动作捕捉在研究中的应用摘录

Nokov 光学三维动作捕捉系统采用高精度的动作捕捉镜头捕捉反光 Marker 点，构建三维数据的动作采集与分析系统，广泛应用于步态康复、运动分析、人机交互等领域。本文通过 Nokov 光学三维动作捕捉系统采集人体步态数据，进行康复训练。系统主要包括 6 个 Mars1.3H 型的光学动作捕捉镜头（1280×1024、1.3MP、240Hz）、两个 Bertec 三维测力平台、动作捕捉软件(Cortex)、反光 Marker 点、标定杆、数据传输设备等，三维动作捕捉系统结构图如图 2 所示。动作捕捉镜头采用十位灰阶深度+GrayScale 图像处理算法的双优组合，云计算，多镜头并联，使 Nokov 光学动作捕捉系统可以进行更精确、更迅速、更稳定的实时运动捕捉，实现亚毫米级的捕捉精度。

引用格式 王瑗珲，葛祎霏，胡宁宁等.基于步态数据的下肢康复机器人控制设计[J].控制工程，2021,28（11）：2266-2272.DOI：10.14107/j.cnki.kzgc.20200552.

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基于非线性变刚度驱动器的膝关节康复外骨骼设计与分析

关键词

膝关节损伤；康复外骨骼；机器人辅助康复；非线性变刚度驱动器；盘式扭簧；

摘要

因中风、脊髓损伤等疾病所引发的膝关节运动功能损伤的情况经常出现,这种情况会使肌肉虚弱或瘫痪的患者无法进行日常生活、活动,而且存在较高的继发二次并发症的风险。对于康复过程中步态失常的患者来说,康复医疗器械,如膝关节康复外骨骼,可以帮助患者进行康复训练,恢复正常步态。膝关节康复外骨骼是可穿戴的人机协作系统,能够在穿戴者的膝关节处产生可控的辅助力矩。相较于传统的人工康复治疗,膝关节康复外骨骼具有康复效率高和康复周期短的特点。在目前的一些膝关节康复外骨骼研究中,大部分驱动器的刚度都是恒定的,或者是刚度变化为线性的,将驱动器的刚度设计为更贴近人体肌肉特性的非线性变化的研究成果较少。本文设计了一种基于非线性变刚度驱动器(Nonlinear Variable Stiffness Actuator)的膝关节康复外骨骼,开展了如下研究:首先,充分了解人体下肢的解剖学结构,探究人体膝关节的运动特性。在充分考虑人体步行的人机工程学和人体下肢生物力学的基础上,设计了膝关节康复外骨骼的仿生机械骨架、可变刚度驱动器(Variable Stiffness Actuator)和非线性变刚度驱动器两种驱动器,建立了膝关节康复外骨骼三维模型,并选定了合适的材料进行加工。本文中采用模块化设计,两种驱动器均可与仿生机械骨架配合安装。其次,基于迭代有限元仿真分析方法设计了膝关节康复外骨骼的弹性元件——盘式扭簧。介绍了盘式扭簧的设计方法,基于 Ansys/Workbench 对盘式扭簧的力矩—挠度特性进行了仿真分析,并通过实验验证了该特性。再次,根据可变刚度驱动器和非线性变刚度驱动器的模型,对驱动器的驱动系统进行建模,通过理论计算对其驱动特性进行分析；并且对可变刚度驱动器和非线性变刚度驱动器进行了动力学建模,基于 MATLAB/Simulink 仿真验证了可变刚度驱动器的可行性和有效性。最后,制作了基于非线性变刚度驱动器的膝关节康复外骨骼物理样机,设计了其控制系统硬件和软件,搭建了实验平台,制定了膝关节康复外骨骼的控制方案,进行了轨迹跟随实验和刚度调节实验,验证了结构设计和控制系统设计的正确性。

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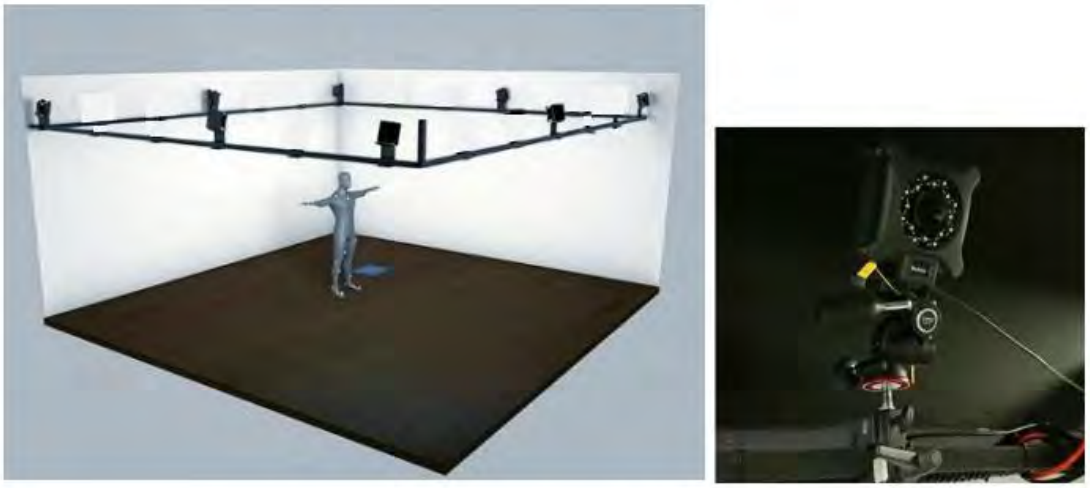

图 2.6 三维动作捕捉系统及红外摄像头

Fig 2.6 3D Motion Capture System and Infrared Camera

NOKOV 度量动作捕捉在研究中的应用摘录

采用北京度量科技有限公司的 NOKOV（度量）光学三维动作捕捉系统对人 体膝关节运动信息采集，如图 2.6 所示。该系统采用高性能红外摄像头可以捕捉 粘贴在人体下肢上的反光标识点，采集并生成精准、实时的人体下肢动作信息， 通过动作捕捉软件 Seeker 对采集到的数据进行处理和分析。在实验中，采用了 8 个摄像头组成的运动捕捉系统，摄像头通过三角伸缩杆均匀放置在实验室的四周， 可以在实验室中央放置一个结构简易的跑步机，让受试者在跑步机上匀速行走， 来达到步态信息采集的目的。

引用格式 王兵.基于非线性变刚度驱动器的膝关节康复外骨骼设计与分析[D].合肥工业大学，2022.DOI：10.27101/d.cnki.ghfgu.2022.000755.

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基于非圆带轮—五杆机构驱动的手指康复装置设计及试验

关键词

非圆带轮-五杆机构；解域综合；关节力；优化；手指康复

摘要

目前手指康复机构多通过尺度综合或采用多自由度机构来实现预期运动，无法同时满足手指康复时对姿态和轨迹的要求。针对该问题，本文提出单自由度非圆带轮-五杆的手指康复机构，通过动捕试验得到手指运动的位姿要求，提取四个重要位姿，基于解域综合方法求解了通过精确四位姿的五杆机构解域；采用非圆带轮约束五杆机构中的两连杆，使之成为单自由度机构。根据手指康复机构的要求并考虑机构的传力特性，建立了机构参数优化模型，优化得到最佳参数。建立了非圆带轮传动计算模型，根据得到的指关节需要满足的转角关系求解非圆带轮廓线。根据得到非圆带轮-五杆机构参数，结合手指康复结构要求，设计并研制了手指康复装置，并进行试验研究。本文的主要研究内容如下：

1）对手指的结构和运动形式进行分析，采用 NOKOV 三维红外被动式光学动作捕捉系统进行手指屈伸运动的数据采集试验。对试验数据进行处理，分别得到标准形式的指尖轨迹散点图和散点分布均匀的关节转角图，为后续机构设计提供参数依据。

2）面向手指的屈伸运动要求，提出了一种适用于手指康复的单自由度非圆带轮-五杆机构及其综合设计方法。提取指尖轨迹上四个重要位姿点，使用解域综合方法求解通过四精确位姿的五杆机构解域；建立关节力分析模型，引入力传递性能指标（机构在外力作用下，运动过程中各转动副内力中的最大值与外力比值的绝对值）对解域进行优选，实现对机构参数的优化。建立非圆带轮传动计算模型，根据指关节间的转角关系求解非圆带轮廓线，并根据康复运动要求完善了非圆带轮机构设计。

3）进行手指康复装置的结构设计，使用 SolidWorks 绘制三维模型，运用 3D 打印技术加工样机主体零部件，并完成康复装置样机的装配。根据指关节安全力矩确定数字舵机型号，通过 PWM 技术实现对舵机转角和转速的控制，完成手指康复装置驱动模块的设计。开展手指康复装置的位姿验证试验，通过对比指尖的实际轨迹和理想轨迹，以及在四个位姿点处的实际参数和理想参数，验证了手指康复机构设计的正确性和可行性；完成指面压力试验，验证了手指康复装置的安全性和可靠性。

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图 2.4　动捕试验环境

NOKOV 度量动作捕捉在研究中的应用摘录

对手指的结构和运动形式进行分析，采用 NOKOV 三维红外被动式光学动作捕捉系统进行手指屈伸运动的数据采集试验。

引用格式 徐袁翔.基于非圆带轮—五杆机构驱动的手指康复装置设计及试验[D].浙江理工大学，2023.DOI：10.27786/d.cnki.gzjlg.2023.000349.

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基于广义回归网络的步态生成

关键词

下肢康复机器人；广义回归；步态生成

摘要

下肢康复机器人可以通过模拟健康人行走的步态来实现康复训练，由于步态参数（节奏、步长、步速等）呈现出多样性和实时在线数据量不足，如何得到合适舒适的指导步态成为现阶段设计基于人体步态特性下肢康复机器人的关键。本文选择了一种广义回归网络作为步态生成的模型，本模型具有强大的非线性映射能力，并且在样本数据量较少时，也能达到更好的预测效果。广义回归神经网络的输入为步长与步速，输出为下肢关节轨迹。测试的结果显示，广义回归神经网络预测出的关节轨迹接近于实验采集的关节轨迹。通过本方法，可以根据患者在不同治疗阶段的特征，制定出不同的康复训练计划。

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图 1-1 步态采集

NOKOV 度量动作捕捉在研究中的应用摘录

本文采用了 NOKOV 三维红外无源光学运动捕捉系统来记录步态，该系统配有 6 个红外摄像机和 2 个测力平台， 图 1-1 所示，将六个标记点贴于人体下肢各个关节外侧，志愿者在此场景内自由行走，动作捕捉系统就会记录下人的步态数据，为了保持步态的自然性，我们没有规定志愿者的脚一定要踩在测力台的中心点。
为了保证数据集的完整性和可用性，从 NOKOV 采集到的原始步态数据经过一系列以下的处理：
1 消除无效的步态数据：由于有一些标记点被遮挡或者是抖动，所以我们要把这些遮挡点移除。
2 滤波：采集的步态数据容易受到周围环境中杂点的影响和减少信号中的噪声数据，采用最小二乘法进行滤波。
3 步态周期的截取：由于人体的步态具有周期性，所以只研究一个步态周期， 通过检测髋关节在整个步态周期的极小值，图 1-2 所示，我们将两个极小值点之间为一个步态周期的髋膝关节变化数据。

引用格式 辛秀芬,王瑗珲,廖伍代等.基于广义回归网络的步态生成[A].中国自动化学会.2021 中国自动化大会论文集[C].中国自动化学会：中国自动化学会，2021：4.DOI：10.26914/c.cnkihy.2021.053571.

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基于人体步态数据的下肢外骨骼动力学建模及应用研究

关键词

下肢外骨骼机器人；动作捕捉系统；动力学建模；控制系统设计；仿人建模与辨识

摘要

下肢外骨骼机器人是一种结合了人体机理与机械特性而开发设计的可穿戴设备，已经被广泛应用在康复治疗、军事、抗震救灾等领域。随着人们对康复治疗需求的提高，下肢外骨骼机器人的研究越来越受到人们的关注。下肢外骨骼机器人可以帮助脊椎受损、脑卒中等中枢神经系统疾病而导致下肢运动障碍的患者进行康复训练。下肢外骨骼机器人可以为患者提供主动和被动两种康复训练模式，对于下肢瘫痪的患者，可以由下肢外骨骼机器人带动患者进行被动式康复训练，对患者早期的康复起到了关键作用；对于下肢没有完全丧失运动能力的患者，下肢外骨骼机器人为患者提供主动训练方式，增加患者参与康复训练的主动性。如何实现仿人平滑控制，使其达到训练舒适有效仍然是现阶段研究和推广应用的热点，而实现舒适有效平滑控制的关键点主要集中在仿人辨识和控制策略上，因此本文针对下肢外骨骼机器人的建模和控制方面的问题开展了研究，主要研究内容如下：

（1）进行了下肢外骨骼机器人系统分析。针对现有的下肢外骨骼系统，分别从机械系统、传感器系统、控制系统、驱动系统和能源系统五个方面进行了详细的分析。

（2）分析了下肢运动规律。基于人体测量学理论，对人体行走规律进行研究，通过动作捕捉系统在建立的动作捕捉现场上测量下肢的运动轨迹，通过求解各关节中心点的轨迹来分析下肢运动规律。

（3）完成了下肢外骨骼动态建模。模仿机器人模型，利用拉格朗日方程推导出下肢外骨骼机器人单侧腿二连杆形式的多输入、多输出和高耦合的非线性动力学模型，并对其动态特性进行了详细的分析。

（4）设计了下肢外骨骼机器人控制系统。为了实现下肢外骨骼机器人能够平稳迅速的跟踪正常人的步态轨迹，分别设计了 PD 控制、自适应控制、鲁棒自适应 PD 控制器。其中，PD 控制在忽略了系统重力和扰动的情况下，可以实现下肢外骨骼机器人定点控制，实现位置和速度的跟踪误差为零。根据下肢外骨骼机器人的动态模型具有不确定性的特点，设计自适应控制系统，实现了跟踪控制效果。考虑到系统与外界的扰动情况，在误差和扰动上界未知的情况下，设计了用鲁棒自适应 PD 控制系统，实现关节角度和角速度快速跟踪。

（5）验证了应用仿人建模方法辨识一种下肢外骨骼机器人动力学模型的有效性。通过反向仿真方法，即人行走的轨迹作为下肢外骨骼机器人控制期望输出，行走时关节力矩作为主要控制输入信号，完成了在模型误差存在的情况下控制效果的仿真，验证了提出方法的有效性。

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图 3.2 定位杆、校正杆和 mark 点（从左到右）

NOKOV 度量动作捕捉在研究中的应用摘录

本文步态数据采集所用的动作捕捉系统为 NOKOV 三维红外被动式光学动作捕捉系统，该系统硬件设备主要由 6 个光学摄像机、mark 点、定位杆、校正杆、数据传输设备、上位机等组成。本文研究所用 NOKOV 三维红外被动式光学动作捕捉系统的镜头为 Mars2 型号，如图 3.1 所示。
Mars2 型号镜头有着较高的捕捉精度，可以实时捕捉表演者的每一个动作，然后通过以太网数据线将实时捕捉到的数据传输给上位机，以太网数据线同时也负责给 Mars2 型号镜头供电，Mars2 型号镜头的主要参数如表 3.1 所示。 其它主要硬件设备如图 3.2 所示，动作捕捉系统中的定位杆主要用来确定整个系统的世界坐标系原点和各轴正方向，其中较长的杆所指的方向就是 x 轴的正方向，与它垂直的杆所指的方向为 y 轴正方向，根据右手定则可以求出 z 轴的正方向；动作捕捉系统中的校正杆用来校验动作捕捉数据的准确度，动作捕捉系统得到的校正杆长度和实际杆长一致则校正通过，可以进行下一步数据采集工作，不一致则无法进行数据采集；mark 点由表面涂有反光物质的小球和底座组成，把它贴在人的下肢各个关节处，人在动作捕捉系统的镜头下行走，就能得到人的运动轨迹。

引用格式 蔡飞.基于人体步态数据的下肢外骨骼动力学建模及应用研究[D].中原工学院,2019.

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基于人体运动步态数据的下肢康复机器人仿人控制

关键词

下肢康复机器人；人体运动机理；步态数据；OpenSim 仿真；仿人控制

摘要

随着社会老龄化人口的加剧和运动障碍疾病患者的增多，导致需要下肢康复训练的人越来越多，康复训练需要逐步纠正或改善病人的行走姿势和步态。众所周知，医生用手动和经验的方式进行辅助性康复训练是最有效的办法，然而康复医生的数量远远不能满足患者的需求。为了减轻医生的工作压力，帮助患者尽快进行康复训练，利用基于人体运动规律设计的仿人下肢康复机器人进行康复训练成为了一个有效途径，已经成为研究热点。因此，如何将人体的运动机理，例如步态数据，进行有效处理并应用到下肢康复机器人设计和控制中，成为实现下肢康复机器人设计和仿人的关键。因此，本文以下肢康复机器人为研究对象，进行了基于人体步态数据的仿人控制研究，主要内容如下:（1）人体运动机理分析。通过动作捕捉系统和测力台设备获取真实的人体步态数据，进行仿机器人动态模型特性分析。考虑采集过程中的外界干扰和人行走过程中的抖动，导致步态运动曲线不平滑问题，首先进行滤波处理，并利用傅利叶拟合方法进行数据整合，为将步态数据应用到下肢康复机器人设计做准备。（2）下肢康复机器人动力学建模。通过模仿多连杆机器人模型，利用拉格朗日方程推导出下肢康复机器人的二连杆非线性模型。针对模型参数不确定性问题，进行了参数结构化处理。（3）基于人体步态的 OpenSim 建模、仿真与控制。本文由动作捕捉系统标定人体模型，经过模型缩放、逆运动学和正向动力学求解得到人体下肢关节角度和力矩，并分析运动规律。控制系统设计中，将 OpenSim 预测的人体运动力矩作为前馈补偿，设计基于步态特性的控制器，完成康复机器人仿人运动。方法验证中，将步态轨迹作为期望轨迹，运动数据输入到 OpenSim 作为控制量，进行反向仿人运动验证，最终结果发现该方法不仅能跟踪人体真实步态轨迹，而且还能使机器人运动的初始力矩变小、舒适度增强。（4）基于真实人体步态的模型不确定康复机器人的自适应控制。本文针对机器人动力学模型不确定问题，设计了一种基于人体步态数据的仿人自适应控制器，分析了系统的鲁棒稳定性。通过仿真结果可知，该方法不仅对机器人模型的不确定部分进行有效补偿，还能有效跟踪人体真实运动步态，提高控制精度。

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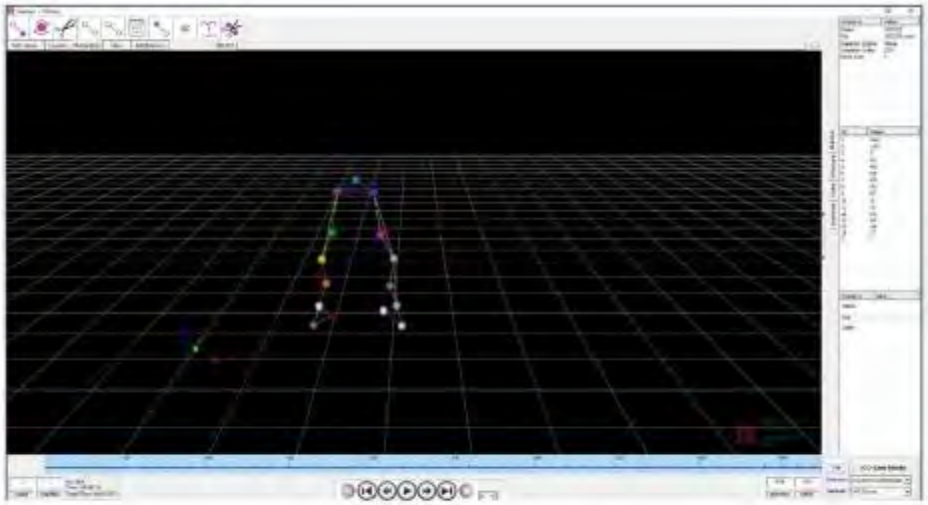

图 2-7 动作捕捉系统软件

NOKOV 度量动作捕捉在研究中的应用摘录

动作捕捉操作及分析处理软件 Nokov，可结合系统中多个镜头获取的二维坐标以及每个镜头在空间中的位置信息，通过软件端的计算，得到六自由度、偏航角、横摇角、俯仰角、欧拉角等数据。同时具备实时处理数据，并支持系统标定、校正及数据采集和导出，并且得到的数据可以通过 VRPN 传输，或通过 SDK（C++语言）端口与 Labview、Matlab 等软件进行再次开发，如图 2-7 所示。

引用格式 卢俊兰.基于人体运动步态数据的下肢康复机器人仿人控制[D].中原工学院, 2021.DOI: 10.27774/d.cnki.gzygx.2021.000203.

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基于人体运动机理的下肢外骨骼机器人控制系统设计

关键词

外骨骼机器人；人体运动机理；运动数据处理；跟踪控制；舒适度评价

摘要

众所周知，通过医务人员的护理和辅助训练来改进患者下肢运动功能是相对安全有效的途径。但是，由于人口老年化问题，患者的增速远远超过为全部运动功能障碍的患者数提供医务人员进行辅助功能训练的能力。基于机器人系统与生物医学工程原理的外骨骼机器人的出现为广大患者带来了福音，能帮助患者在无人照顾情况下进行一定程度的有效康复训练。通过外骨骼机器人康复训练使患者下肢能像健康人一样运动或行走是设计下肢康复机器人的目的。因此，可以反过来将人体的步态运动特性经过优化处理后用于下肢康复机器人的仿人控制器设计和实时训练中。如何对捕获的运动特性进行有效处理，设计仿人控制器，并将其应用于下肢康复机器人实时辅助训练中，已经成为现阶段下肢康复机器人设计和控制的一个研究热点。因此，本文基于人体的运动机理进行下肢外骨骼机器人动力学建模和控制系统设计展开相关研究。主要研究内容包括：(1) 基于人体运动特性的下肢动力学与运行学分析。本文采用 NOKOV 三维红外式动作捕捉设备和三维测力平台设备进行人体的步态运动数据和足底力数据采集。由于采集过程中受到外界扰动的影响，故利用最小二乘法和最小滤波法对数据进行滤波处理。由于处理后的数据无法直接应用于下肢外骨骼机器人作为理想参考运动，因此通过对高斯函数、傅里叶函数和正弦函数三种方法的拟合系数和均方根误差对比与分析，采用傅利叶函数进行曲线拟合，拟合后的曲线作为下肢外骨骼机器人控制系统的参考期望运动轨迹，并对采集到的数据进行人体运动学及动力学特性分析。（2）仿机器人机构的下肢动力学建模。本文选取下肢外骨骼机器人的左腿进行研究，通过模仿多连杆机器人结构，利用 Lagrange 方程推导出下肢外骨骼机器人动力学模型，详细分析其动态特性，通过系统的线性化特性将下肢外骨骼机器人模型的已知参数和未知参数进行分离，最终得到系统的线性化模型。（3）基于人体运动机理的下肢外骨骼机器人控制系统设计。结合人体下肢的运动机理特性对外骨骼机器人控制系统进行研究，本文提出基于人体舒适度的线性反馈控制、基于人体舒适度的自适应控制、基于人体步态数据的鲁棒自适应 PD 控制三种方法。基于人体舒适度的线性反馈控制方法主要以人体穿戴下肢外骨骼机器人舒适度为目标函数，对非线性系统进行线性化。针对机器人参数不确定问题，采用基于人体舒适度的自适应控制方法进行解决，通过设计的自适应率可以对系统惯性参数进行很好的辨识。针对系统的外界干扰及输入力矩过大的问题采用基于人体步态数据的鲁棒自适应 PD 控制解决，通过仿真结果可知在系统误差和扰动上界已知的情况下下肢外骨骼机器人控制系统仍然具有较好的稳定性，且改善了前两种方法控制输入力矩过大的问题。通过相似性函数验证机器人运动轨迹与人体运动轨迹相似极高，客观表明人体穿戴过程中的舒适性。稳定条件都通过 Lyapunov 定理进行了推导，同时讨论了轨

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迹跟踪特性。（4）基于实验数据的下肢外骨骼机器人控制系统仿真验证。为了验证提出理论的有效性，本文将采集到的下肢运动特性作为下肢外骨骼机器人控制系统的参考期望运动轨迹，进行了基于实验数据的下肢外骨骼机器人控制系统仿真验证。

a. L 型标定杆　　b. T 型标定杆

图 3.2 标定杆

NOKOV 度量动作捕捉在研究中的应用摘录

通过国内动作捕捉系统的对比，本文采用效果较好的 NOKOV 三维红外被动式光学动作捕捉系统，其系统组件主要由 6 个 Mars2H 镜头（如图 3.1 所示）、连接器、三脚架、三向云台、连接线、标定杆（T 型、L 型标定杆如图 3.2 所示）、NK_Cortex 软件、反光标志点（Marker）等组成。本文采用动作捕捉系统采用被动式红外光原理设计\[58]，系统采样频率可自行调节，
Mars2H 镜头参数如表 3.1 所示，捕捉精度较高且延迟时间短，采用频率可根据实验要求实时调节，高功率的 HLED 发光器，让光源更集中且高效耐用，摄像机镜头内有图像处理器，可以保证采集到的数据经云计算后实时传输，摄像头采用并线连接方式，在确保高实时性的同时提高了系统稳定性。

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基于人体运动特性的个性化步态生成与预测研究

关键词

步态生成；步态预测；下肢康复机器人；卷积神经网络；注意力机制

摘要

随着科学技术的进步和康复理念的更新，将康复理论知识融入机器人设计，以机器 人技术助力康复事业的双向融合模式成为了康复医疗发展的重要推动力。下肢康复机器 人是应用于下肢康复训练的辅具，实用性强，应用前景广阔。在训练中，机器人紧贴患 者下肢，为患者提供支撑和引导，在减轻患者下肢负担的同时带动患者运动。鉴于机器 人和患者的运动高度耦合，让机器人的运动与患者的步态相匹配，理解患者意图，成为 了进一步提高康复效果和训练舒适度的关键。本文从人的运动特性出发，开展了应用于 下肢康复机器人的个性化步态生成和步态预测研究，具体工作内容如下： （1）采集，处理并分析步态数据。本文使用三维动作捕捉设备和三维测力平台搭建 步态采集系统，共收集了 74 位健康志愿者的身体物理参数数据、关节运动数据和足底 压力数据。以真实数据为基础，探究人体下肢的运动规律，构建了步态数据集，为后续 工作提供数据和理论支撑。 （2）将个体身体差异量化为步态差异，以身体物理参数为基础，个性化地生成步态 轨迹。本文根据傅里叶函数的周期特性，以傅里叶拟合参数代表髋关节和膝关节运动轨 迹，并设计了以一维卷积为主干的步态生成模型。该模型以为身体物理参数和期望步态 参数为输入，以傅里叶拟合参数为输出。在模型的训练中，借助结构重参数化思想，采 用了多分枝模型训练，单路模型推理的方式。对比实验结果显示，该模型具有收敛快、 泛化能力强的优点。模型生成的轨迹误差小，符合人的步态趋势，能够作为下肢康复机 器人运动的参考轨迹，从而为患者提供定制化的康复服务。 （3）基于足底压力与姿态之间的联系，以足底压力数据预测未来关节角度变化。本 文提出了步态预测模型 TFSformer，以建立足底压力和关节数据之间的映射。在模型的 编码器部分，使用一维卷积操作从时间维度和力空间维度综合提取步态特征。在解码器 部分，在注意力机制的基础上，设计了多通道注意力机制和深层多通道注意力结构。此 外，使用变分模态分解方法对输入数据进行处理。对比实验证明本文模型能够稳定地预 测未来髋关节和膝关节角度变化趋势。未来步态是人运动意图的体现。步态预测工作能 够将穿戴者的历史运动信息中蕴含的抽象的运动意图具体化，以此补偿传感器延迟，为 康复机器人控制器的实时优化提供依据。

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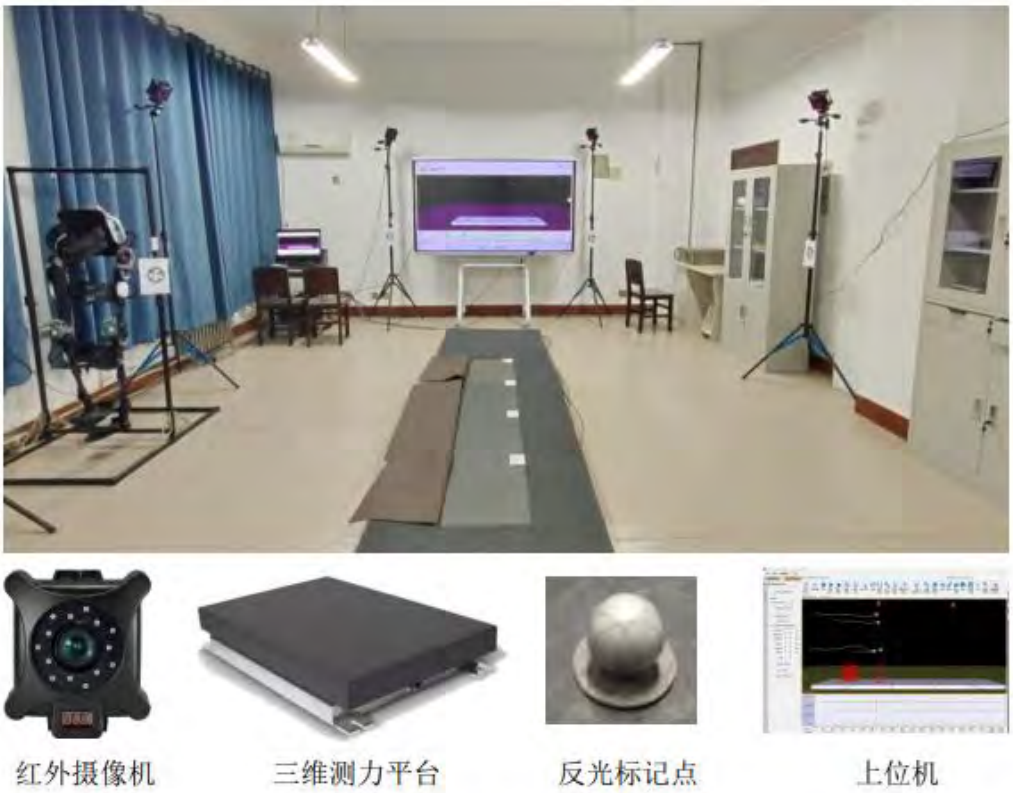

图 2-1 实验系统构建图

NOKOV 度量动作捕捉在研究中的应用摘录

为准确采集关节数据与足底压力数据，本文使用 Nokov3D 红外被动光学动作 捕捉系统和 Bertec 三维测力平台共同搭建实验环境，采集场景如图 2-1 所示。 Nokov3D 红外光学动作捕捉系统具有精度高、实时性强，支持多目标捕捉等优势。 此系统配备的红外摄像头具备 1200 万像素的高分辨率和最高 300 帧每秒的高捕捉率，能够实现亚毫米级的捕捉精度。系统利用摄像机阵列和红外反射器，通过观测目标物体 表面的反射点在多个摄像机视角下的位置，实现对目标物体在三维空间中运动的精确追踪。捕捉的数据在经过时间同步后，系统进一步将二维图像坐标转换为三维坐标，实现对目标物体的实时更新和建模。

引用格式 任迦乐.基于人体运动特性的个性化步态生成与预测研究[D].中原工学院,2024.DOI:10.27774/d.cnki.gzygx.2024.000509.

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基于任务导向训练的上肢康复路径规划与动作分类方法研究

关键词

任务导向训练；路径规划；归零神经网络；动作分类；深度学习

摘要

近年来,心脑血管疾病造成偏瘫和运动功能障碍等中枢神经损伤的患者逐年增加且日渐年轻化,中枢神经系统损伤后,神经组织再生需要被其他高级中枢神经系统代偿而得到恢复,基于大脑的神经可塑性,上肢康复机器人可进行特定的运动功能训练帮助患者实现肢体康复,但现有的上肢康复训练方案在个性化定制和实用性方面仍有不足。为更好的帮助患者恢复正常的运动功能,本文从人体上肢运动特征输出函数、上肢康复机器人路径优化和人体上肢康复动作分类三方面展开研究,其主要研究工作如下:(1)针对日常生活任务导向训练问题,从解剖学和生物力学角度分析人体上肢骨骼和肌肉结构,通过光学动作捕捉系统采集人体上肢康复运动数据,从预处理后的数据中生成康复运动的人体上肢运动表征,用于寻找人体运动学输出作为人体运动框架的内在特征,获得人体上肢运动特征输出函数,为实现基于任务导向训练的康复路径规划方法研究奠定基础。(2)针对上肢最优康复训练路径问题,结合关节活动度技术,基于患者不同时期的康复状态,通过在不同康复阶段调整康复训练任务,使用不同的训练难度刺激不同肌群的恢复,重塑中枢神经系统对患肢的支配与控制。设计基于人体工学和康复医学的综合康复指标约束上肢运动特征输出函数,采用归零神经网络求解时变非线性约束优化问题,获得可根据患者当前康复阶段自主调节训练难度的上肢康复训练的最优路径。基于任务导向训练的上肢康复训练最优路径可应用于康复机器人的路径规划,提高康复训练效率,保证上肢康复有效性和舒适性。(3)针对跨个体上肢动作分类问题,通过采集人体上肢肩部、肘部及腕部在进行上肢康复训练时产生的表面肌电信号并提取信号特征,建立基于卷积神经网络的动作分类模型,对上肢康复运动进行动作识别并完成动作分类。实验结果表明,基于深度学习的动作分类模型具有良好的分类效果。为实现患者在临床应用的有效性,使用神经网络剪枝实现网络轻量化,减小神经网络模型的大小和占用空间,增加上肢康复动作分类模型的实时性,为上肢康复机器人实现临床应用奠定基础。

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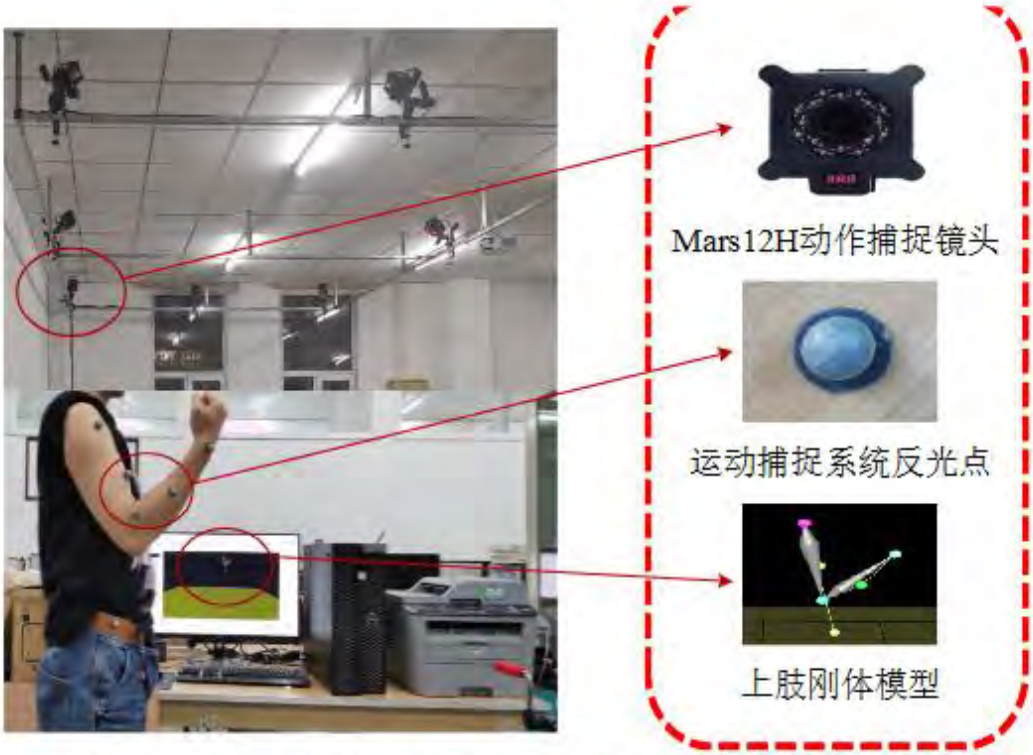

图 3-1 基于 NOKOV 光学动作捕捉系统的数据采集实验

NOKOV 度量动作捕捉在研究中的应用摘录

> *基于 NOKOV 光学三维动作捕捉系统的数据采集实验如图 3-1 所示。使用了 8 台 Mars12H 动作捕捉镜头，Mars12H 动作捕捉镜头分辨率为 1200 万像素，频率 300Hz，3D 测量值精度在 0.2mm 以内。*

引用格式 严杨犇. 基于任务导向训练的上肢康复路径规划与动作分类方法研究[D].长春工业大学,2023.DOI:10.27805/d.cnki.gccgy.2023.000453.

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基于深度神经网络的骨折复位机器人路径规划研究

关键词

机器人辅助手术；深度学习；路径规划；深度神经网络；股骨骨折

摘要

近年来随着全球人口老龄化日益加剧以及现代交通运输业迅猛发展，骨科疾患呈逐年增加的趋势。研究表明骨折已经成为影响人类生活的常见病和多发病，人类大腿骨、股骨骨折发病率约为 37 例 / 10 万人。由于目前临床采用的闭合复位和切开复位分别存在准确度低和创伤大等缺点，外科医生和研究人员开始致力于将机器人应用于骨折复位手术，但由于骨折环境复杂，断骨之间的精准对齐及复位路径的规划仍是亟待解决的难题。因此，本文基于深度神经网络对机械臂辅助骨折复位系统的复位路径进行了规划，以提高复位的精度和自动化程度。

本文选择光学三维动作捕捉系统作为采集手段，使用人类股骨、固定夹具、标定球支架、标定球和上位机系统搭建了采集骨折复位路径信息的实验平台，在专业骨科医师的指导下设计了符合临床需求的断骨复位路径采集方案，并完成了路径采集实验。采集的数据经过修补完善后作为深度神经网络模型的数据集，供模型学习骨折复位路径的规律。

基于深度神经网络模型进行复位路径预测，对建立模型所需要确定的超参数进行理论分析，选取平均绝对误差作为损失函数，以最小化损失函数值作为优化目标，通过正交试验，对比确定了包括神经网络的层数、各层神经网络神经元数量、激活函数、学习一率、次训练选择的样本数量（批量大小）等超参数，建立了用于预测骨折复位路径的深度神经网络模型，并对其进行训练。

为验证深度神经网络模型的学习效果，本文搭建了验证实验平台，依次进行路径规划和复位执行两个步骤，将五组不同的股骨骨折情况作为深度神经网络模型的输入，在机械臂与上位机系统通信的情况下，将深度神经网络模型规划出的复位路径点直接输出给机械臂，在机械臂系统自带的碰撞检测功能和实验者的监督下进行复位移动以评估深度神经网络模型规划的复位路径的有效性和准确性。

验证实验结果表明，利用所提出的深度神经网络模型规划获得的路径是安全可靠的。深度神经网络模型输出的最终位姿点与理想目标位姿点在位置和姿态上的平均误差分别为 0 .067mm 和 0.036°。在利用机械臂辅助执行复位时，用理想的目标位姿点替换最终位姿点，进一步降低实际误差。实际复位过程中还包含机械臂累积误差、环境误差等，最终点位置和姿态的实际平均误差分别为 0 .163mm 和 0.223°，复位时间平均为 10.612 秒，并且复位趋势符合牵拉-对线-复位的基本规律，过程中无碰撞或划痕。这对骨折复位机器人系统未来的临床应用具有重要意义。

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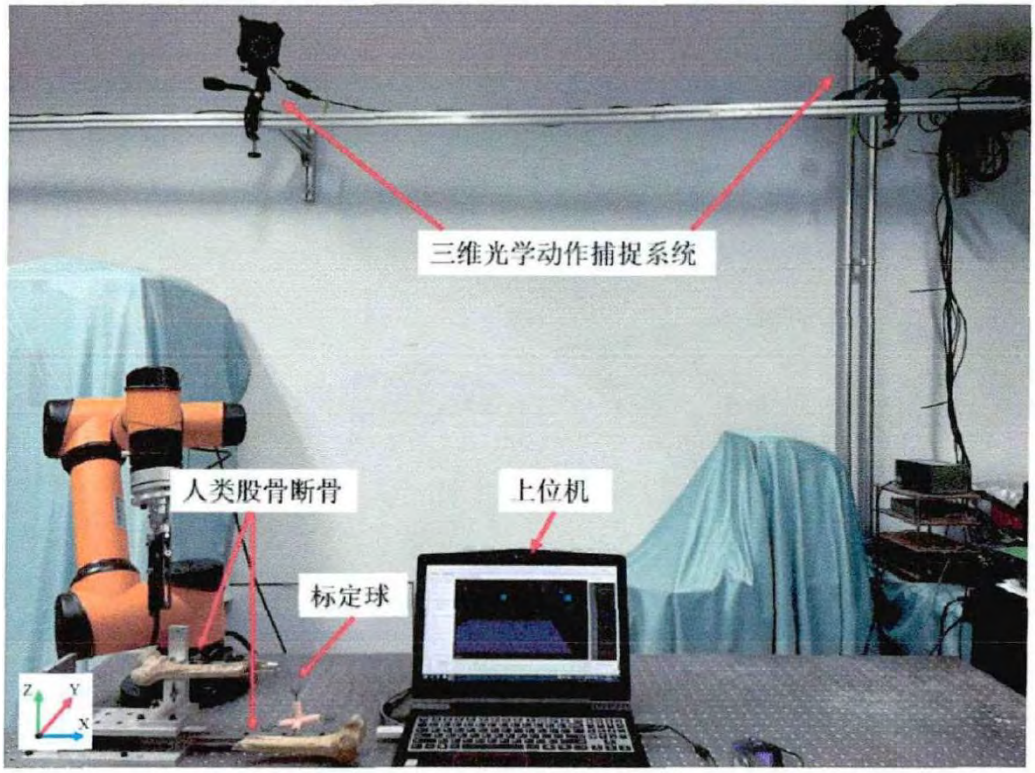

图 3-1 路径采集平台示意图

Fig. 3-1 Path acquisition platform

NOKOV 度量动作捕捉在研究中的应用摘录

基于八镜头 NOKOV 三维动作捕捉系统搭建了路径采集实验平台，在骨科医师的指导下设计采集实验方案，手持远端断骨对各类情况下的骨折复位路径进行演示，在三维动作捕捉系统中结合采集到的标定球信息建立刚体，将刚体复位路径的位置和姿态六个自由度的数据输出。
本实验选择的光学动作捕捉系统是八镜头 NOKOV 光学三维动作捕捉系统，采集精度为± 0.15mm。捕捉系统配备了专门的数据分析软件，可以输出.csv 格式的数据文件。通过光学 3 D运动捕捉系统实时捕捉标记的位置。

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基于特征对齐的机器人辅助脱衣抓取点识别方法研究

关键词

抓取点识别；卷积神经网络；机器人辅助脱衣；人机交互

摘要

全球范围内人口老龄化、劳动力短缺等社会问题的日趋严重推动了辅助型机器人领域的快速发展,面向用户日常生活的各类服务型智能机器人如康复治疗、交流陪伴、辅助穿衣机器人等应运而生,机器人辅助穿脱衣物因其在日常生活中的高度实用性而逐渐成为研究热点。然而,有关辅助脱衣的研究却尚未完全开展。本文拟利用人型机器人辅助医疗工作者脱去医疗衣物,以期在一定程度上缓解医疗工作者的工作及健康压力。除此之外,本文未来也可进一步延伸应用场景至家庭环境中,帮助老年人、残障人群提供多种类型衣物的辅助脱衣服务,具有较高的实用价值与应用前景。研究者通常通过赋予机器人多种感知能力,使其在近距离的人机交互中操控非刚性、高维度的衣物从而实现辅助用户穿衣的过程。本文的核心问题是通过训练视觉模型从而为机器人提供用户肩部的抓取信息。实际上,视觉模型的训练通常依赖高质量的标记数据,因此,需要在前期工作中采集大量真实图片数据并进行标记。然而,带有标记的真实数据的采集既耗时,又难以获取。相比于真实数据,易于大量获取的合成数据能够有效扩充难以采集的真实数据。但是,合成数据的作用存在一定的限制,这是因为真实数据与合成数据之间天然存在的领域差异(例如数据分布等)极大弱化了合成数据对于模型的性能提升。为了克服这一限制,本文提出了一个合成-真实对齐网络(Syn-to-Real Alignment Network,SRAN)。在网络设计上,对齐网络不仅在特征层面上利用可形变卷积(Deformable Convolution,DConv)自适应地对齐合成图片和真实图片,以弥补领域差距,同时通过 Mixup 方法与卷积模块为对齐图片生成合理分布的伪标签。接着将对齐网络生成的对齐图片应用于基于卷积神经网络的抓取点识别模型进行训练,在模型性能的评估中,验证了对齐网络在缩小域差异、提高识别抓取点准确性方面的显著作用。进一步地,为了将抓取点模型在真实实验中进行部署验证,本文设计了一个机器人辅助脱衣系统。该系统首先进行衣物分类,接着使用抓取点模型识别出实时图片的抓取点信息,最后,机器人通过路径规划完成整体的脱衣工作。实时实验表明,所提出的脱衣系统可以使机器人能够对衣物的类别进行分类并识别出抓取点,为真实用户提供辅助脱衣的服务。

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图 3.4　采集真实数据的环境配置

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由于在为用户完成脱衣的过程中，用户的不同姿态会对双肩的抓取点产生影响，如遮挡抓取点。因此，需要在使用 Kinect 获得高质量深度图片的同时，借助 NOKOV 光学三维动作捕捉系统在三维空间中实现高精度的实时室内定位与运动追踪，对用户肩部的位姿数据等运动学数据进行采集。动作捕捉系统实时收集每张深度图片对应的坐标信息，同时使用 NOKOV 公司提供的软件对初始采集到的原始数据在可视化的三维空间中进行显示。

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基于运动意图理解的上肢康复机器人机构设计与协同控制

关键词

上肢康复机器人；重力平衡；运动意图识别；表面肌电信号；人机协同控制

摘要

随着社会人口老龄化加剧,由于脑卒中导致运动功能障碍患者数量增加。为帮助上肢运动功能障碍患者进行康复训练,国内外研究者设计了多种上肢康复辅助装置,其中上肢康复机器人成为康复医疗领域研究热点。上肢康复机器人不仅能够帮助受试者进行有效康复运动,同时还可以缓解医疗资源紧缺问题,促进医疗资源合理分配。上肢康复机器人是人机一体化康复设备,理想状态下上肢康复机器人不仅具有符合人体工学结构,并且具备识别人体上肢运动意图能力和安全柔顺人机协同运动性能,为受试者提供安全舒适的康复训练环境。本文针对上肢康复机器人机构设计与人机协同控制算法研究,首先设计重力平衡式仿生上肢康复机器人结构并进行有限元分析和动力学分析,其次采用表面肌电信号识别人体上肢运动意图,再次提出上肢康复机器人人机协同控制算法,最后开展基于人机协同控制系统的人体上肢单关节和多关节康复训练实验研究。本文的主要研究内容及取得的创新性成果如下:(1)设计了一款重力平衡式仿生上肢康复机器人结构。针对上肢康复机器人自重较大问题,本文提出一种重力平衡式仿生上肢康复机器人,为受试者提供安全舒适的康复训练环境。首先根据上肢解剖学,从仿生学角度进行上肢康复机器人柔顺化结构设计,上肢康复机器人前臂结构仿生人体上肢前臂骨骼结构,避免上肢康复机器人和受试者上肢产生人机对抗冲突；其次设计重力平衡结构,防止上肢康复机器人因自重过大造成人体上肢肌肉损伤；再次对上肢康复机器人主要受力部件进行有限元分析,保证受试者康复训练安全性；此外分析重力平衡结构合理性,进行上肢康复机器人重力平衡结构的仿真实验验证和平台实验验证,验证重力平衡结构能够有效地抵消上肢康复机器人大部分重力；最后利用拉格朗日方法建立重力平衡式仿生上肢康复机器人动力学模型,为上肢康复机器人驱动系统的选择和控制系统的设计提供基础。(2)提出了一种基于表面肌电信号的上肢运动意图识别方法。针对提高上肢运动意图识别准确性问题,本文提出一种基于长短期记忆神经网络和归零算法模型相结合的上肢运动意图识别模型。首先基于表面肌电信号产生机理,使用无线生理数据采集设备采集受试者上肢运动相关肌肉群的表面肌电信号,结合角度传感器实时获取受试者上肢运动角度和角速度,将表面肌电信号和运动信息作为运动意图识别信号；其次利用长短期记忆神经网络建立开环预测模型识别受试者上肢单关节运动意图,并且选择合适的神经网络参数提高运动意图识别的准确性；再次将长短期记忆神经网络和归零算法模型相结合建立闭环预测模型识别多样本受试者上肢多关节运动意图,确定表面肌电信号、关节力矩、关节运动角度和运动角速度之间映射关系,并且闭环预测模型消除开环预测模型的预测误差,提高上肢多关节运动意图识别的准确性；最后开展上肢多关节运动意图识别实验和临床实验数据分析,通过对比开环预测模型和闭环预测模型预测结果,验证闭环预测模型准

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确性、可行性和优越性。获得科学研究项目伦理审查意见后,进行上肢多关节运动意图识别临床实验数据分析,验证闭环预测模型可以有效进行上肢运动功能障碍患者的运动意图识别。(3)提出了上肢康复机器人一种人机协同控制方法。针对上肢康复机器人轨迹跟踪问题,本文利用比例-微分控制算法设计上肢康复机器人控制器,仿真实验实现上肢康复机器人对期望轨迹的稳定跟踪。针对提高人机协同控制系统快速收敛性能和稳定跟踪性能问题,本文提出一种上肢康复机器人人机协同控制方法,首先基于人机协同控制系统动力学模型和上肢多关节运动意图,利用归零神经动力系统设计人机协同控制方法,消除系统中不确定因素,保证人机协同控制系统具有良好的收敛速度和稳定的跟踪性能；其次提出一种具有归零神经动力系统和扰动观测器的迭代学习控制方法,利用归零神经动力系统消除系统中不确定因素,利用扰动观测器消除系统中外部干扰,利用迭代学习控制实现重复性康复训练动作,保证人机协同控制系统具有抗干扰能力、快速收敛性能和稳定跟踪性能；再次利用李雅普诺夫理论证明人机协同控制系统的稳定性；最后实验验证所提出的人机协同控制方法可行性和有效性。(4)上肢康复机器人实验平台搭建和上肢康复训练实验研究。为满足受试者上肢康复训练需求,首先搭建上肢康复机器人实验平台,包括搭建硬件系统和设计控制系统；其次进行上肢康复机器人系统空载实验,研究上肢康复机器人系统的跟踪性能和动态响应性能；再次进行上肢康复训练实验,利用人机协同控制方法进行上肢康复机器人系统实验研究,人机协同控制方法可以实现上肢康复机器人的稳定跟踪性能,实验验证上肢康复机器人系统可以实现不同模式下单关节和多关节的康复训练活动；最后进行上肢康复机器人性能评估,验证受试者上肢康复训练效果。基于上述研究,受试者在康复训练过程中,人机协同系统可以准确识别受试者运动意图,有效地控制上肢康复机器人运动,提升上肢康复机器人的实用性和适用性,从而实现上肢康复机器人和受试者之间的协同运动。

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NOKOV 度量动作捕捉在研究中的应用摘录

利用 NOKOV 光学动作捕捉系统获取上肢康复机器人工作空间，光学动作捕捉系统是以红外光学为原理的动作捕捉系统，具有精度高、延迟低、实时性强、多用于室内场景等特点，图 2.16 为 NOKOV 光学动作捕捉系统获取上肢康复机器人工作空间实验，受试者穿戴上肢康复机器人进行空间运动。图 2.17 为利用 NOKOV 光学动作捕捉系统获取上肢康复机器人工作空间。

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具备人机耦合性瞬心旋转膝关节矫形器设计

关键词

膝关节屈曲;膝关节矫形器;瞬心轨迹;轨迹发生法;四杆机构;人机耦合;动作捕捉;有限元仿真;

摘要

针对膝关节屈曲功能障碍患者的康复治疗问题，基于人体膝关节运动瞬心的曲线轨迹，设计一种具备人机耦合性的瞬心旋转膝关节矫形器。通过动作捕捉实验，采集膝关节屈曲运动瞬心轨迹作为机构设计的目标轨迹，然后基于轨迹发生综合方法，进行四杆机构数学模型和矫形器结构建模。通过运动学仿真与肌骨模型的有限元分析，验证矫形器与传统铰链矫形器在还原膝关节旋转瞬心轨迹、应力分布方面的显著优势。最后，进行样机实验，采集矫形器矫形过程中的膝关节瞬心轨迹，整体拟合程度较好，可实现对膝关节的精准矫治，矫形过程中的矫形力较传统铰链式矫形器降低 6 N，具备较好的人机耦合性，可提升患者在膝关节矫治康复过程中的舒适度，为临床康复提供精准化的治疗方案。

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图 1 膝关节瞬心提取实验

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1 膝关节屈曲运动捕捉及轨迹分析
为获取人体膝关节屈曲运动过程中瞬心运动轨迹，设计三维动作捕捉实验，采用间接测量的方式获取。实验选取 5 名体态健康志愿者，身高 165-175 cm、体重 65-75 kg。采用 Nokov 公司生产的 MARS2H 动作捕捉设备，围绕采集区域均匀放置 8 个摄像头，调整每个摄像头使其捕捉范围能完整覆盖采集区域。以志愿者左腿作为研究对象，在人体矢状面内佩戴标记点[16]。实验要求志愿者坐在实验台上，大腿始终与实验台贴合，小腿绕膝关节自由转动，身体在运动过程中保持自然放松状态实验数据正式采集前，志愿者进行多次模拟练习熟悉实验流程。坐标系原点 0 建在实验台桌角轴方向平行于实验台，方向垂直于实验台，人体面向坐标系的轴的反向，如图 1(a)中所示。在大腿和小腿外侧粘贴两块竹板，将标记点粘贴在竹板上，以减弱肌肉抖动对实验结果产生的影响[17-18]。竹板的平面平行于坐标系的 XO, 平面，标记点沿竹板边缘对称粘贴，每块竹板上贴有 4 个标记点，小腿上分别粘贴标记点 1、2、3、4，大腿上分别粘贴标记点 5、6、7、8，如图 1(b)所示。

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可穿戴下肢外骨骼康复机器人设计及运动特性研究

关键词

下肢外骨骼康复机器人；运动特性；人机协同；运动仿真

摘要

为了对下肢运动失能患者完成康复训练,且在保证功能实现的前提下满足良好的人机协同性,本文研究了人体下肢的运动机理和人体步态,对下肢外骨骼康复机器人的主被动自由度、驱动方式、长度调节等方面进行了对比分析,考虑了安全性和舒适性,设计了下肢外骨骼康复机器人的机械本体结构,并完成了虚拟样机的三维设计。基于 ANSYS 仿真软件,进行了下肢外骨骼康复机器人的静力学分析,验证了外骨骼机械结构的刚度,并进行了下肢外骨骼康复机器人的模态分析,验证了人机系统运动过程的稳定性。研究中将外骨骼机器人模型进行简化并建立了运动学 D-H 模型,对其进行了正、逆向运动学分析,得到了关节角度与位姿之间的关系；借助 MATLAB 仿真软件建立了外骨骼机械腿仿真模型,验证了正向和逆向运动学数学模型的正确性,并采用蒙特卡洛法得到了外骨骼机器人的工作空间。基于拉格朗日动力学方法,建立了行走姿态下人机耦合系统的动力学方程,并加入了踝足部模块的动力学模型,得到了人机系统各关节的力矩表达式,增加了动力学模型的完整性,使其更具备现实意义。基于 ADAMS 仿真软件,对人机耦合系统模型进行了虚拟样机仿真分析,得到了外骨骼机器人各质心的运动曲线、关节角度、力矩等,并分析对比了人体下肢与外骨骼机器人的运动结果,验证了人机具有良好的协同性。最后,搭建了人体步态实验数据采集平台,设计并加工了人体直线行走步道,通过动作捕捉系统记录了人体在平地正常行走时的运动数据,并对数据进行了处理分析,对比分析了虚拟样机仿真结果与步态实验结果中髋、膝关节的角度变化,验证了虚拟样机仿真模型的正确性。

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图 5.10　平地直线行走实验

NOKOV 度量动作捕捉在研究中的应用摘录

光学式运动捕捉系统是应用最为广泛的运动捕捉技术，具有捕捉范围大、采样速率高、精度高、使用方便等优点。通过对国内外动作捕捉进行对比研究，本实验选择 NOKOV 三维红外光学动作捕捉系统，采集获取正常人体步态运动的相关数据。其系统主要由 Mars1.3H 数字动作捕捉镜头、反光标记点、系统标定杆、摄像供电系统、POE 交换机和分离器、连接光缆组成。

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末端牵引式手指康复机器人机构优化设计

关键词

康复机器人；手指康复；参数优化；曲柄滑块机构；光学动作捕捉；仿真分析

摘要

手指康复机器人是用于辅助患者手部进行康复运动的设备，为了使手指康复机器人满足康复需求，首先分析人手生理 结构特点及关节转动范围，通过光学动作捕捉实验得到手指末端运动轨迹。为了满足这一运动轨迹，提出一种由曲柄滑块和末 端斜杆组成的末端牵引式手指康复机器人机构。然后通过优化曲柄滑块机构尺寸参数，使机构更加紧凑。优化末端斜杆的长度 和角度参数，使其末端运动轨迹满足手指康复运动需求。最后通过仿真验证了机构的正确性。

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(a) NOKOV 三维光学动作捕捉实验室

(b) Marker 点

图 1 光学动作捕捉系统

NOKOV 度量动作捕捉在研究中的应用摘录

为了得到手指末端运动轨迹，进行了光学动作捕捉实验，以获得手指屈伸运动的真实曲线。通过表 1 得到的中国成年人手指指骨长度范围，选取符合条件的志愿者，志愿者手指指骨长度，如表 2 所示。为每个标记点定义了一组坐标，实验所用设备为 NOKOV 三维光学动作捕捉系统，实验室，如图 1（a）所示。采集的反光标记点 Marker 点，如图 1（b）所示。该系统通过 NOKOVMars4H 摄像机精准的采集反光标记点 Marker 点运动过程中的空间坐标。实验正是运用该原理，对志愿者手部粘贴的 Marker 点进行追踪来完成手指运动光学动作捕捉实验。

引用格式 王志军,姚贺元,李占贤,等. 末端牵引式手指康复机器人机构优化设计[J]. 机械设计与制造,2025(11):353-358. DOI:10.3969/j.issn.1001-3997.2025.11.065.

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跑台式下肢外骨骼康复机器人机构及控制策略研究

关键词

下肢外骨骼康复机器人;重心起伏;减重步行训练;粒子群优化;

摘要

我国逐步步入老龄化社会,心脑血管疾病和脑卒中的发病率持续攀升,且患者年龄呈现出年轻化倾向,大部分下肢运动功能障碍患者存在下肢肌力不足、偏瘫等现象,为解决下肢运动功能障碍患者无法独立保持站立平衡的问题,设计一款具有动态减重系统的跑台式下肢外骨骼康复机器人,该动态减重系统具有重心跟随功能,可根据患者需求选择不同的预减重值,给予患者精确、个性化的减重训练方案。本文主要研究内容如下: 1.跑台式下肢外骨骼康复机器人结构设计。基于人体下肢解剖学与运动机理,开展动态减重和下肢外骨骼两部分的机构设计。依据人体下肢生物力学参数,设计了与人体关节自由度匹配的下肢外骨骼机构;结合步态康复训练中人体重心动态变化特征,设计了具有实时补偿功能的悬吊式动态减重机构。 2.机器人系统运动学、动力学建模。首先,为求得下肢外骨骼各关节的运动关系,采用 D-H 法对机器人下肢外骨骼系统进行运动学建模,减重机构则通过笛卡尔坐标系对它和被试者进行运动学建模;其次,采用拉格朗日法对下肢外骨骼系统建立动力学模型,并且针对动态减重系统,将其简化为弹簧-阻尼模型,建立动力学模型。最后,通过 ADAMS 软件搭建虚拟样机进行仿真分析,验证所建立的数学模型的正确性,为后期研究提供理论基础。 3.机器人系统控制策略设计。针对下肢外骨骼系统,设计基于模糊滑模控制的轨迹跟踪控制器,利用其强鲁棒性特点实现关节运动轨迹的精确跟踪。针对动态减重系统,提出粒子群优化(PSO)改良的模糊 PID 控制算法,通过 PSO 算法优化模糊 PID 控制器的量化因子和比例因子,实现对人体重心轨迹的稳定跟踪。在此基础上,引入力反馈补偿环节,通过实时检测人体减重值变化并调整减重力,消除重心移动带来的减重值误差,提升系统动态减重性能。最后,基于系统传递函数和期望重心轨迹在 Simulink 中搭建仿真平台,通过轨迹曲线的对比验证了控制策略可行性与稳定性。 4.样机搭建与实验分析。首先,搭建跑台式下肢外骨骼康复机器人实验样机并设计电气系统,通过电机轨迹跟踪实验,验证了基于 PSO 寻优算法的模糊 PID 控制下的位置跟踪有效性。其次,为研究冠状面和矢状面上的偏移角度对垂直轴上位移的影响,进行实验,结果表明冠状面与矢状面的偏移角度影响可以忽略。接着,根据临床使用需求设计减重实验,通过对比预减重值和实际减重值的一致性来证明动态减重系统在动态补偿过程中的稳定性。再次,通过下肢外骨骼的轨迹跟踪实验,验证模糊滑模控制器的有效性。最后,通过减重系统与外骨骼系统协同实验,验证其协同工作时的稳定性。

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图 4-1 动作捕捉场景

NOKOV 度量动作捕捉在研究中的应用摘录

> *4.2 下肢姿态数据采集与处理*
> *在进行控制策略研究前，需要确定其系统输入。为了使仿真更符合实际工况，均采用实际重心轨迹曲线和髋、膝关节曲线作为系统输入。本实验采用北京度量科技的 Nokov 三维红外光学运动捕捉系统采集人体运动时重心的变化数据，通过滤波拟合后的轨迹曲线作为减重系统控制器的数据输入。该系统主要由主机服务器、8 台光学摄像机、反光小球（常称 Mark 点）、T 形校准条、L 形校准条、控制器等部分组成。光学摄像机记录所有标记的空间坐标，分辨率为 200 万像素，捕获频率为 60HZ，人体运动轨迹捕获精度可达 1mm。光学相机内采用并线连接，在保证实时性的同时也保证了数据采集时系统的稳定性。*

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七自由度上肢康复机器人的设计与研究

关键词

上肢康复机器人；偏瘫；机构设计；机器人控制系统

摘要

我国正处于人口加速老龄化阶段,因脑卒中产生的偏瘫患者数量庞大且逐年递增,这对我国的康复医疗体系提出了严峻的考验。本课题以提高偏瘫康复效果和减轻康复医师短缺现状为目标,研制了一款基于人体上肢生理学运动特性的七自由度上肢康复机器人。具体内容如下:首先,对现有上肢康复机器人机构特点进行归纳总结。基于上肢生理学运动特性以及偏瘫康复理论,提出上肢康复机器人的设计要求,并制定总体方案。其次,根据总体方案,设计上肢康复机器人的各关节构型。借助平行四边形能够转移旋转中心的特点,设计了一种新型肩带机构与腕部机构。结合常用上肢康复动作与我国成年人上肢运动范围,确定康复机器人的各部分尺寸、传动方式以及各零件的选型,并使用 Solidworks 软件完成机器人建模。然后,设计并搭建康复机器人的控制系统。针对力矩传感器噪声问题,使用快速傅里叶变换进行谱分析并设计滤波器完成降噪。在实时操作系统下移植 Ether CAT 协议栈,使用 Ec-master 配置各驱动器的 PDO 参数,实现了上位机对驱动器底层参数的实时控制。通过康复机器人描述文件,在 Simscape 环境搭建了仿真模型,通过正运动学算法验证了模型的正确性。为下位机控制软件配置了包含康复机器人通讯协议、关节、运动学、外部 I/O 等参数的 YAML 描述文件。最后,对康复机器人关键部位进行静强度分析,并完成整机模态仿真。在先前搭建的仿真环境下完成静力仿真,验证了各关节选型的合理性。使用动捕系统采集人体上肢动作,用于康复机器人辅助训练仿真与轨迹跟踪仿真。仿真结果表明,康复机器人能够复现常用康复动作并具有良好的轨迹跟踪性能。

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图 5-16　度量（NOKOV）动作捕捉系统组成

NOKOV 度量动作捕捉在研究中的应用摘录

本次实验采用的是度量公司（NOKOV）的光学动作捕捉系统，主要包括数据处理的上位机部分、数据传输的下位机部分以及数据采集的硬件部分。如图 5-16 所示，数据采集的硬件部分主要由 8 个在圆周方向均匀分布的镜头及其支架组成，其中镜头自带红外光发射单元；数据传输的下位机部分是 POE 交换机（支持以太网供电），保持了目前技术成熟的以太网 Cat.5 架构，协议上没有作任何的改动，在为上位机传输数据信息的同时，也为数据采集的硬件部分供电；数据处理的上位机部分是安装在 PC 端的软件。

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人体特征融合下的康复机器人控制器设计

关键词

下肢康复机器人；人体步态数据；RBF 神经网络；智能控制；深度强化学习；

摘要

当前我国已成为老年人口最多的国家之一,老年人也是各种疾病的高发群体,特别是能引起下肢功能性障碍的脑卒中和神经损伤性疾病。下肢功能性障碍给患者带来了巨大的生活困难和压力,有研究表明康复医疗可以一定程度上恢复患者的运动功能。现有的康复师和康复医疗资源远远不能满足患者的需求,康复机器人的出现可以一定程度上缓解医疗资源短缺的现象,有些方面还超过了康复技师的治疗效果。因此,康复机器人技术的研究引起了众多学者的关注,其中康复机器人控制系统成为当前研究的热点之一。在保证安全性和可靠性的前提下,机器人控制器的仿人化和智能化设计成为提升下肢康复机器人有效性和安全性的新突破点。因此本文做了以下相关研究:

（1）引入人体步态运动特征到下肢康复机器人控制系统设计中,达到其仿人化和智能化功能。首先,使用三维动作捕捉系统构建出人体步态数据采集空间。然后,采集人体在采集空间中行走的步态数据。最后,通过滤波、优化等一系列的运动学计算,得到人体关节角度的数据,进而规划出适用于康复训练的仿人化参考轨迹。同时由足底力的数据计算出关节力矩,并将其运用在控制器的设计上,使得下肢康复机器人能像人体一样运动,增加患者康复中的舒适度。

（2）基于对人体步态数据分析的结果,设计基于滑模的神经网络控制和基于人体步态的仿人滑模神经网络控制。下肢康复机器人是一个复杂非线性系统,易受外界干扰。机器人的模型建立是一相当困难的工作。因此本研究使用了 Radialbasisfunction（RBF）神经网络来降低机器人建模的难度。同时使用滑模控制以达到快速跟踪参考轨迹的目的。经过仿真验证两种控制方法都能快速跟踪期望轨迹,并表现出一定程度的仿人性。为改进提出方法的有效性,定义了一种新的舒适度评价函数,以此评价控制效果。结果发现基于人体步态的仿人滑模神经网络控制在舒适度方面有着一定的优势,同时跟踪误差较小,收敛的速度也较快。

（3）人类步态既有规律性和多样性,又具有一定的差异性。康复机器人需要表现出人体步态的这些特征,进而实现仿人化和智能化的目的。因此,提出了一种基于人脑学习机制的深度强化学习算法与 PD 控制器相结合的仿人控制系统。该控制器通过学习人体步态特征来规划康复训练的步态轨迹,不仅增强了机器人的智能化和仿人功能,而且保证了康复过程中的安全性。

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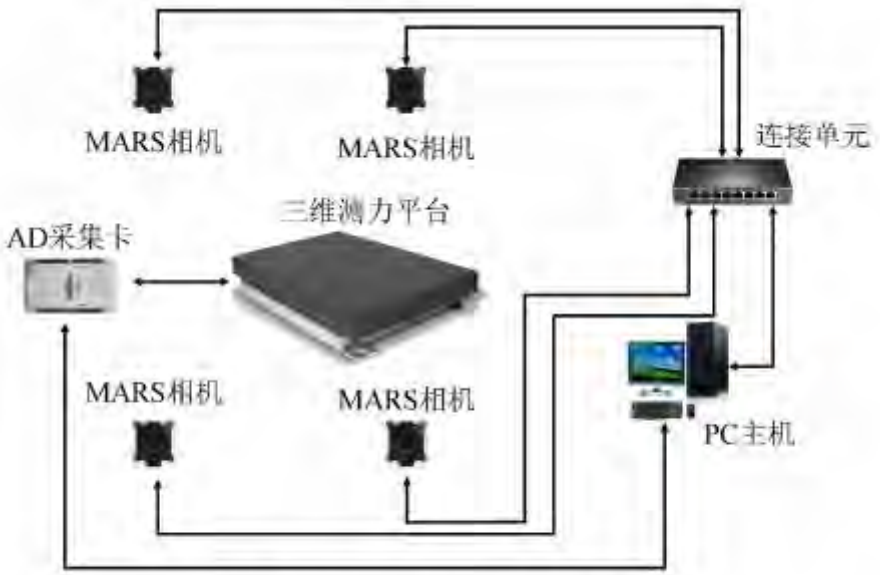

图 3.1 Nokov 运动捕捉系统

NOKOV 度量动作捕捉在研究中的应用摘录

本文使用 Nokov 运动捕捉系统来采集人体步态数据，如图 3.1 所示。该系统是一种光学式捕捉系统。图 3.2 展示了组成部件:光学红外镜头、反光标记点、两根标定杆。Nokov 系统使用 MARS 相机的分辨率高达 1200 万像素，测量精度达 0.08mm，而延迟仅为 3.0ms。Nokov 系统作为一个实时应用系统，可以在 PC 端实时查看动作捕捉的图形结果，后续能以几种文件格式保存捕捉数据。此外，该系统使用 Cortex 软件以图形化方式编辑采集的数据，无需借助于额外的软件包。系统设置和校准都能快速和简单的完成，同时具有即时反馈的功能。而且该系统也包含数据预处理功能，该功能以图形化方式呈现，可以快速和直观的对采集的数据进行编辑。而且通过 AD 采集卡和三维测力平台，该系统可以同步测得人体行走过程中的足底力的变化。因此该系统能够满足动作捕捉的精度和实时输出的要求，这使得该系统成为 3D 动画的一个合适的引擎，也被本文所使用。

引用格式 李伟.人体特征融合下的康复机器人控制器设计[D].中原工学院，2022.DOI：10.27774/d.cnki.gzygx.2022.000219.

链接

https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CMFD&dbname=CMFDTEMP&filename=1022512324.nh&v=MjAyMjM1SExhNUhOTE9xNUViUElSOGVYMUx1eFlTN0RoMVQzcVRyV00xRnJDVVI3aWZZT1JwRnk3aFc3L0pWRjI=

人体下肢数据采集及下肢康复轨迹跟踪控制研究

关键词

数据采集；OpenPose；轨迹跟踪；模糊 PID；粒子群算法

摘要

人体下肢康复是康复医疗的一个重要分支,旨在协助患者完成重复性的下肢运动训练,恢复其一定的行动能力,提高患者生活质量。在患者治疗过程中主要涉及下肢数据采集和康复训练两部分。本文首先提出一种非接触式的人体数据采集系统,采集得到的数据可用于指导下肢运动障碍患者康复训练。然后对索驱动下肢康复机器人的轨迹跟踪控制进行研究,并设计实验验证研究内容。论文的具体研究内容如下:提出一种基于计算机图像和 Open Pose 人体姿态识别算法的非接触式人体数据采集方法。基于 Open Pose 搭建人体姿态识别程序,实现对图像中人体关节数据的提取工作。为了实现实时的人体姿态识别,需要提高算法对固定分辨率图像的识别速度,结合感兴趣区域(Region Of Interest,ROI)及人体数据采集实验的特性,从减少被处理图像的信息量的角度,对 Open Pose 人体姿态识别算法进行改进,提高人体姿态识别程序的整体运行速度。设计了可以实时采集人体个性化参数的数据采集系统。利用所提出的数据采集方法和深度相机,分别获取人体关节点的像素坐标信息及其对应的深度信息,对相机参数进行标定,完成关节点空间坐标的重建任务,实时解算各段肢体的长度及各个关节的转动角度。为人体数据采集系统设计简洁的 UI 界面,能够直观地显示测量数据,并将转角数据绘制成波形图,方便观察各关节的运动轨迹。使用该系统完成了人体下肢个性参数及运动数据的采集工作,与现有的人体下肢运动数据集进行对比,验证了该采集系统的有效性。针对索驱动下肢康复机器人提出了一种基于粒子群优化的模糊 PID 控制方案。建立了索驱动下肢康复机器人的运动学模型,在仿真环境下分别设计并使用 PID 控制器和模糊 PID 控制器进行了轨迹跟踪仿真,证明了模糊 PID 控制的优越性。为了得到更好的轨迹跟踪效果,利用粒子群算法对模糊 PID 控制器的比例、量化因子进行优化,仿真结果证明经过优化后的模糊 PID 控制器能够取得更好的跟踪效果。搭建了下肢康复系统实验样机并进行轨迹跟踪控制实验。针对绳索缠绕不均匀的问题,设计了绳索定点绕放机构。基于光学三维动作捕捉系统编写了测量线程,基于固高运动控制系统编写了控制线程,解决了测量线程与控制线程之间的数据通信问题,实现了闭环控制。最后进行轨迹跟踪控制实验,实验过程中利用人体数据采集系统实时远程传输下肢的运动数据和图像,实现远程观测。实验结果证明了基于粒子群优化的模糊 PID 控制器能够有效提高索驱动下肢康复机器人的轨迹跟踪精度。

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图2.3 Nokov 系统硬件组成

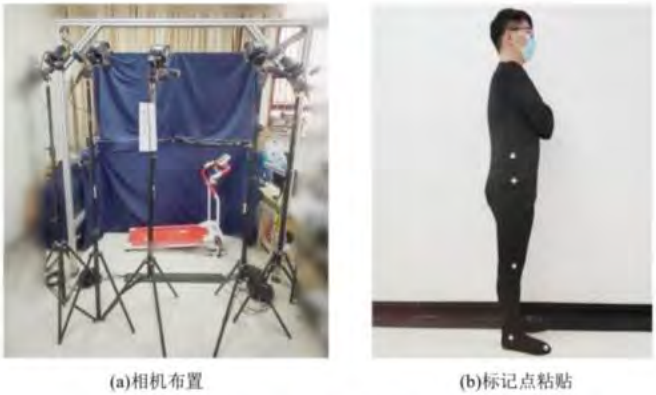

图2.4 Nokov 三维动作捕捉系统实验环境

NOKOV 度量动作捕捉在研究中的应用摘录

以北京度量科技有限公司研发的 Nokov 光学三维动作捕捉系统为例，系统硬件 主要有红外相机、反光标记点、相机支架、网络组件和标定体，如图 2.3 所示。
本文选用精 度达亚毫米级的 Nokov 光学三维动作捕捉系统测量下肢运动过程中的姿态数据。测 量线程是在 Nokov 系统自带软件 Cortex 的基础上，使用 Nokov_SDK 对 Nokov 系统 进行的二次开发。控制线程在接收到测量线程传输的数据后，根据控制逻辑进行数学 计算，并将计算得到的控制量发送给运动控制器，驱动电机执行相应的运动。下肢康 复系统软件中各模块关系如图 5.10 所示。

引用格式 郭宁博.人体下肢数据采集及下肢康复轨迹跟踪控制研究[D].西安电子科技大学，2022.DOI：10.27389/d.cnki.gxadu.2022.002189.

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柔顺串联弹性驱动器设计与交互控制方法研究

关键词

柔顺串联弹性驱动器；最优控制；抗噪归零神经网络；交互控制

摘要

伴随着老龄化时代到来,由中风造成肢体残障人数迅速增长。传统康复训练存在训练模式单一、康复周期长、效果不佳等缺点,因此康复机器人在促进患者神经重塑、提升患者康复训练效果和提高患者生活质量等方面具有重要意义。目前,大部分康复机器人采用刚性驱动,具有位置控制精度高等优点,然而仅仅基于位置控制不足以保障患者安全。因此,研究具有安全性、柔顺性和力感知等特性的康复机器人是智能医疗康复领域研究热点。本文针对柔顺串联弹性驱动器结构和交互控制算法等方面进行研究。本文的主要研究内容如下:(1)设计一款新型柔顺串联弹性驱动器结构。针对刚性驱动器无法保证受试者安全问题,结合人体步态生物力学,提出一种新型柔顺串联弹性驱动器,为康复机器人输出柔性动力。在驱动器有限空间内通过使用蜗轮蜗杆减速装置,提高驱动器的输出扭矩,使用齿轮齿条作为传动装置提高驱动器的承载能力。使用扭簧和压簧装置为驱动器提供安全的柔性动力。基于质量弹簧阻尼系统模型,考虑蜗轮蜗杆减速装置、齿轮齿条装置之间的交互力和驱动器各零件间引起的干扰,建立驱动器动力学模型。(2)提出一种线性二次型(Linear Quadratic,LQ)最优控制算法。针对比例-积分-微分(Proportion Integral Differential,PID)控制方法参数调节问题,提出一种最优控制算法,通过选择合适权重矩阵获取最优参数,使柔顺串联弹性驱动器实现精确力控制,并结合数值仿真实验和平台实验验证最优控制器的有效性。(3)提出一种抗噪归零神经网络(Noise-Tolerant Zeroing Neural Network,NTZNN)控制算法。针对柔顺串联弹性驱动器工作中存在的机械结构误差、机械振动和信号干扰等扰动,提出一种 NTZNN 控制器。通过与传统归零神经网络(Original Zeroing Neural Network,OZNN)控制器对比,验证 NTZNN 控制器不仅可以抑制各种混合噪声,还可以提高驱动器系统的收敛性、稳定性和鲁棒性。(4)提出一种人机交互控制算法。基于柔顺串联弹性驱动器动力学模型,提出一种双模态交互控制器,设计非线性扰动观测器提高控制器的鲁棒性。通过数值仿真实验和平台实验验证所设计的控制器具有低输出阻抗特性,能够实现精确输出力控制,提高人机交互的安全性和相容性。

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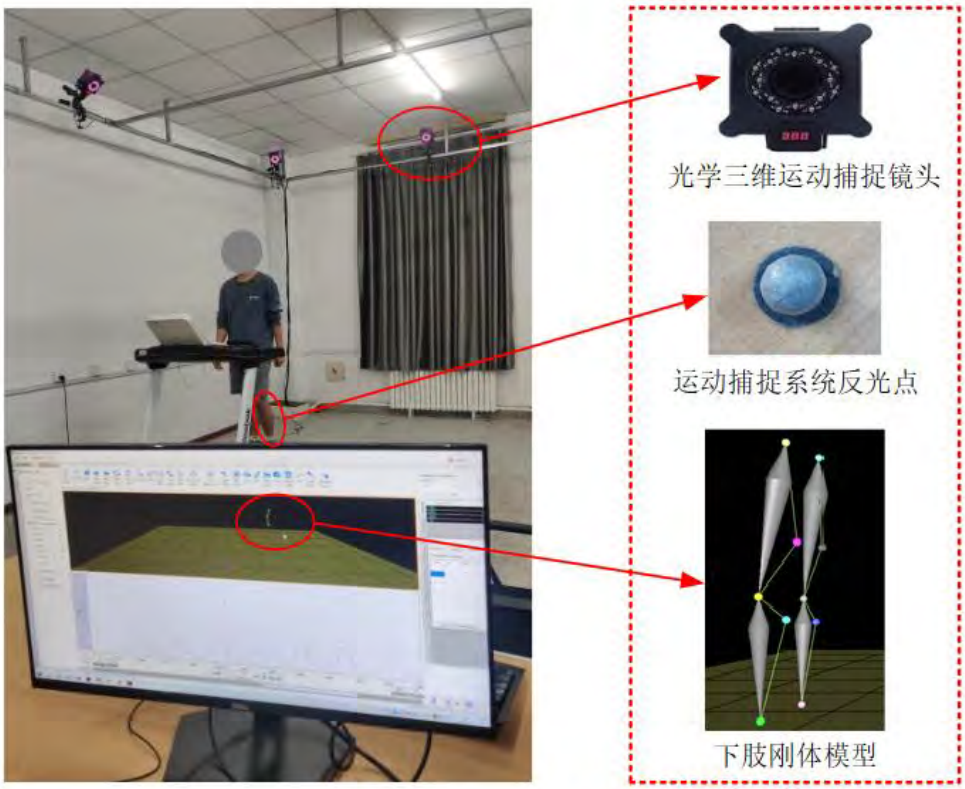

图 5-41 NOKOV 光学动作捕捉系统

NOKOV 度量动作捕捉在研究中的应用摘录

本文通过光学动作捕捉系统采集人体下肢运动角度数据。如图 5-41 表示基于 NOKOV 光学动作捕捉系统采集正常受试者下肢关节角度的实验场景。光学动作捕捉系统用于捕获人类肢体关节角度数据，通过采集受试者完成康复动作时的关节角度并作为任务描述，对所采集数据进行傅里叶拟合得到动作路径的规范化函数，并根据健康受试者生理信息指标定肢体康复期望轨迹。

引用格式 许长贤. 柔顺串联弹性驱动器设计与交互控制方法研究[D]. 长春工业大学,2023.DOI:10.27805/d.cnki.gccgy.2023.000459.

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三自由度下肢康复机器人轨迹规划研究

关键词

康复机器人；轨迹规划；动作捕捉；遗传算法；仿真；

摘要

随着现代机器人学和医疗行业的迅速发展,使用康复机器人对下肢运动损伤患者的治疗成为国内外研究热点之一。为实现更好的康复治疗效果,本课题对一种三自由度下肢康复机器人开展轨迹规划研究,模拟健康下肢关节运动规律,对下肢康复机器人的运动轨迹进行优化设计。基于膝关节、踝关节的康复、损伤机理和运动形式,对比分析几种少自由度平面对称并联机构,确定了以 2UU-UPU 机构作为康复执行机构的设计原型,开展了运动学分析,使用闭环矢量法求解机构的位置逆解,引入数值算例对位置结果进行验证,通过极限边界搜索法研究了该机构的工作空间。对下肢康复机器人开展下肢康复训练的轨迹规划研究,推导了多项式运动规律、摆线运动规律、叠加摆线运动规律的轨迹规划运动公式,并验证在不同康复训练条件下轨迹的合理性。为进一步探究更合理的康复轨迹,使用光学动作捕捉系统采集坐姿状态下的踝关节运动轨迹,建立了康复轨迹约束条件,使用遗传算法对动作捕捉轨迹进行优化,提高了规划轨迹与人体动作的相似度,实现更好的康复效果。进行 Adams-Simulink 联合仿真,建立了基于 PID 控制的控制系统,开展下肢康复机器人轨迹规划仿真实验。通过运动学位置逆解求解电机转角,使用 Adams 软件进行踝关节连续背屈、跖屈运动和连续内翻、跖屈、外翻、内翻复合运动的下肢虚拟康复实验,记录动平台的运动轨迹,仿真结果表明,康复机器人动平台运动轨迹与下肢运动轨迹一致,下肢康复机器人满足康复运动训练要求。图 87 幅；表 8 个；参 59 篇。

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图 44　光学镜头

图 45　反光标记点

NOKOV 度量动作捕捉在研究中的应用摘录

光学镜头（图 44）作为动作捕捉系统的核心，本次实验使用的光学镜头采用 的是 NOKOV 度量科技公司的红外线动作捕捉镜头，型号为 Mars4H，最大分辨率 400 万像素，最大分辨率下最大采集频率 180Hz，该镜头表面有多颗可发射特定波 长的红外 LED 灯，这些红外光照射到附有反光材料的反光标记点（图 45），就可 将红外光反射回动捕镜头，镜头接收到反射回的数据后通过系统内部的图像抓取、 算法处理获取每个反光标记点的二维坐标。通过一套系统中多个镜头的自身位置标 定和实验空间三维位置标定，通过算法获取到每个标记点的三维坐标。

引用格式 杨中原.三自由度下肢康复机器人轨迹规划研究[D].华北理工大学，2022.DOI：10.27108/d.cnki.ghelu.2022.000142.

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绳牵引式上肢康复机器人控制系统设计与验证

关键词

上肢康复机器人；计算机可编程自动化控制器；动作捕捉

摘要

针对自主开发的六自由度绳索牵引式上肢康复机器人本体，设计了一种基于伺服电机和计算机可编程自动化控制器（CPAC）的多电机控制系统。系统由上位机模块、控制模块、执行模块等组成。针对单关节、多关节康复训练动作，分别采用 Jog 运动模式和 Follow 运动模式，结合插补算法实现了康复动作的控制；并借助光学动作捕捉系统验证了控制系统的准确性、稳定性。结果表明:单关节、多关节动作的最大绝对误差分别不超过 5 mm 和 6 mm，随着康复训练动作角速度的增加，最大绝对误差虽有所增大，但增幅较为平缓，这表明控制系统能够实现对单关节、多关节康复训练动作的准确、柔顺控制。

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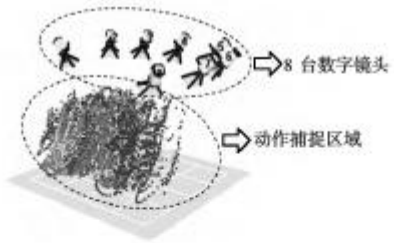

图 6　标定后的捕捉空间

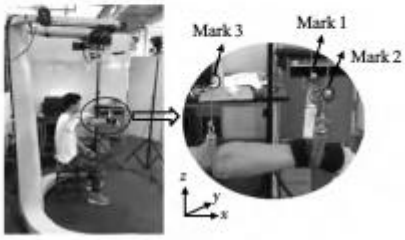

图 7　上肢 Mark 点布置示意

NOKOV 度量动作捕捉在研究中的应用摘录

选用北京度量科技公司的 Nokov(度量)光学三维动作捕捉系统对康复训练进行实验数据采集分析。标定后的动作捕捉空间如图 6 所示，覆盖了上肢康复训练动作的整个运动域。以上肢水平悬吊为初始状态构建 X-Y-Z 空间坐标系，关节标记点布置如图 7 所示，其中，标记点 Mark1 和 Mark2 用于获取腕关节运动数据，Mark3 用于获取肘关节运动数据。鉴于动作捕捉系统采集人体数据的精确度达到亚毫米级，而康复训练动作较为平缓，所以每秒拍摄 60 帧即可。

引用格式 张成杰，刘妤，杨岩等.绳牵引式上肢康复机器人控制系统设计与验证[J].传感器与微系统，2021,40（08）：96-99+103.DOI：10.13873/J.1000-9787（2021）08-0096-04.

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双支链式侧翻辅助装置机构设计与运动学图形表征分析

关键词

侧翻辅助；人体重心运动轨迹分析；双支链结构；运动学图形表征分析；机构构型

摘要

定期侧翻是长期卧床患者预防压疮的重要护理措施，现有侧翻辅助装置机械式结构刚性较大，未考虑人体侧翻运动机理，充气式存在人体关节转动中心和机构转动中心不一致，易导致患者在侧翻过程中受伤，因此，研究人机运动协同的仰卧位侧翻辅助装置设计具有十分重要的意义。依据人体侧翻运动机理的研究基础，设计了一种由平面连杆机构驱动双支链结构的侧翻辅助装置，主要受力位置为肩部和臀部，通过建立数学模型并推导设计参数，利用图解法分析连杆传动角，同时进行装置的运动学仿真、工作空间分析与人体侧翻重心轨迹提取实验，对整体装置进行运动学图形表征分析。结果表明：辅助人体侧翻角度为 30°~45°，该角度范围内人体与双支链接触应力分布较为均匀，有助于预防压疮。机构传动角范围为 42.19°~90°，该角度范围机构具有良好的传力性能。研究验证了装置设计的合理性，双支链结构能够拟合肩部和臀部的运动过程，提供多段式支撑链接触，避免局部压力集中，符合人-机协同性与人机工程学的康复辅具设计要求，为侧翻康复研究奠定了基础。

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双支链式侧翻辅助装置实验台

图 15　双支链式侧翻辅助装置实验台

NOKOV 度量动作捕捉在研究中的应用摘录

> *为验证辅助侧翻机构设计的合理性以及运动学建模的准确性，设计肩部以及臀部支链运动捕捉实验。实验人员平躺在实验平台上，场地中央为主要数据采集区域，八台 Nokov 动作捕捉相机围绕采集区域均匀放置，相机采集频率为 100Hz。调整每个动作捕捉摄像头直至整体捕捉范围能完整覆盖采集区域，实验场地布置如图 15 所示。*

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TKA 术后康复辅具设计及实验研究

关键词

全膝关节置换术；辅助康复训练；康复辅具；肌电实验；性能验证

摘要

全膝关节置换术（Total Knee Arthroplasty, TKA）是一种广泛应用于治疗严重膝关节 疾病的外科手术。TKA 能够有效减轻疼痛并恢复患者的关节功能，但需要接受完善严格 的康复训练过程才能达到最佳术后治疗效果。目前传统的康复训练依赖于人工指导，其进 度和效果往往受到主观因素的影响，并且缺乏精确的量化评估手段。为了解决这些问题， 本文提出了一种主被动一体式康复辅助装置，旨在通过人体生物力学相关分析，得到满足 TKA 术后主、被动训练的康复需求，实现针对性康复训练，从而提高术后康复效率和康 复效果。研究主要包括以下几个方面：（1）下肢康复需求与生物力学建模：结合下肢结构、膝关节周围肌力特征及下肢运 动特性，将 TKA 康复训练依据患者生理特征状态划分为不同康复阶段，系统性整理归纳 不同康复阶段的训练需求，将康复训练划分为术前初期、术前后期、术后初期及术后后期 四个具体阶段，并提出不同阶段的康复需求。结合人体鲁棒模型与笛卡尔坐标系，简化人 体下肢结构从而建立下肢骑行运动数学模型，并推导得出人体下肢可达域模型，为后续装 置的参数设计提供数据支撑。（2）下肢康复训练模拟与实验研究：结合下肢的结构特征和运动特性，基于 Anybody 仿真环境，构建人体下肢肌骨模型，以行走、骑行等目标动作作为模拟驱动，结合逆动力 学分析得到相关肌群激活程度结果。同时，使用表面肌电分析系统采集对应肌群数据并分 析，联动 AnyBody 仿真结果进行模型效能的对比分析，验证所构建人体下肢肌骨模型有 效性。据此，通过人体仿真和肌电实验，分别分析变曲柄、变阻尼、变转速等不同条件下 骑行运动的关节角(Pos)、关节角速度(Vel)、关节角加速度(Acc)、肌肉力(Fm)、肌肉激活 程度(Activity)变化，确立了主、被动训练所需关键参数，如活动范围和阻尼，为后续康复 辅助装置提供设计依据。 （3）TKA 术后康复辅具设计：根据患者 TKA 术后下肢肌力和关节活动度的康复训 练需求，康复辅具优化仿真模拟结果，进行康复训练运动轨迹的分析与参数计算，得出目 标康复训练运动轨迹曲线。通过尺寸参数计算以及 Matlab 软件装置运行轨迹计算，设计 出对应康复训练的传动、阻尼机构，以满足 TKA 术后不同康复阶段对于肌力、膝关节活动角度范围的康复需求，完成整体 TKA 术后康复辅具设计。 （4）康复辅具性能仿真与实验研究：借助虚拟样机进行运动算例计算，驱动模拟对 应运动轨迹，完成运动学仿真，得出角度变化特征，验证机构运行轨迹。对比验证现有骑 行康复装置与本文优化装置的相关性能，设置对照组，结合肌电设备采集下肢目标肌群生 理信号，对比分析对应肌肉激活程度，完成对所设计的康复辅助装置的性能评价，验证装 置的可行性。 论文提出了一种结合逆动力学仿真模拟的康复训练装置设计方法，通过 AnyBody 环 境下仿真模拟与实验研究揭示了下肢骑行运动范围、速度、阻尼与肌群激活程度之间的规 律，以

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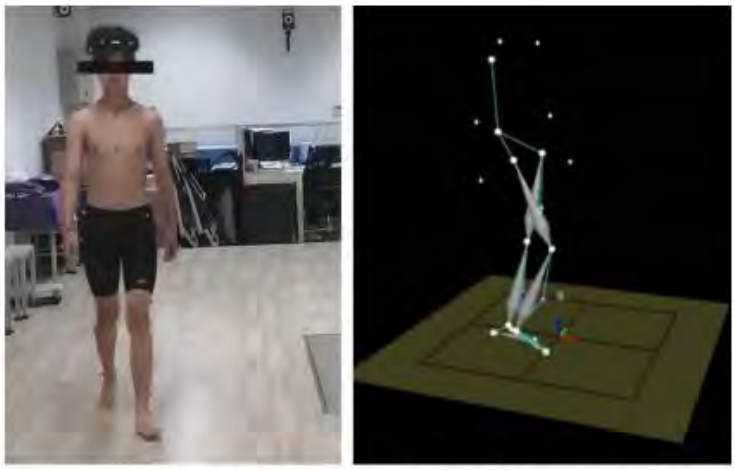
此为基础设计了一种能实现类三角形运动轨迹特点的可变曲柄下肢骑行训练装置， 并通过骑行训练实验，对装置的合理性与可行性进行了验证。



(a) 三维动作采集过程　　(b) 动捕标记点数据处理

(a) 3D Motion Capture Process　　(b) Motion Capture Marker Data Processing

图 3-4 步态运动三维动作数据采集与处理

Fig. 3-4 Collection and Processing of Three-Dimensional Motion Data in Gait Analysis

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本文中动作数据采集实验中所使用设备为（NOKOV 度量光学三维动作捕捉设备，北京度量科技股份有限公司，中国北京）NOKOV 三维动作捕捉系统。三维动作捕捉系统的原理是通过空间中不同位置安放的多个动作捕捉镜头对反光标志点的位置数据进行采集，将复数二维平面坐标系中位移数据进行整合分析，从而计算得出标记点精确三维空间坐标。在实际动作捕捉采集过程中，系统能同时追踪并记录复数标记点位移数据，并可以通过软件对点位数据进行处理与分析。

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索驱动下肢康复机器人误差建模及其补偿研究

关键词

索驱动下肢康复机器人；差分进化；误差建模；灵敏度；误差补偿；

摘要

索驱动机器人是利用柔索代替刚性连杆的一类并联机器人,具备结构简单、大工作空间、易重构等优点。但索作为柔性件,导致索驱动机器人在运动过程中易产生运动误差,因此对索驱动机器人进行误差分析和补偿是必不可少的。本文针对索驱动下肢康复机器人做了以下研究。

本文的索驱动机器人是一种使用四根索牵引人体下肢进行步态训练的康复机器人,也称索驱动下肢康复机器人。为了提高机器人的运动精度,先建立其全参数几何误差模型以及误差灵敏度模型,然后基于各误差源的灵敏度系数筛选出主要误差源,最后通过对主要误差源进行误差辨识以及误差补偿,达到提高机器人运动精度的目的。

首先,采集人体步态轨迹并对机器人进行配置优化和运动学分析。由于该机器人主要用于人体下肢康复训练,因此,第一步利用光学三维测量系统获得人正常行走的步态轨迹。第二步基于该步态轨迹,以工作空间最大化为优化目标,对机器人的结构参数进行优化。第三步在该配置的基础上,对该机器人进行运动学分析,并使用 CASPR（Cable Robot Analysis and Simulation Platform For Research）软件的仿真结果进行对比验证。

其次,优化关节夹角步态轨迹。在保证机器人可以完成康复训练的同时,为了减少运动过程中因振荡造成的能量消耗,提高机器人的运行效率和稳定性,在不偏离理论关节轨迹的基础上,利用差分进化算法,以能量最低为优化目标优化出机器人关节夹角的最优轨迹。

然后,建立机器人全参数几何误差模型以及灵敏度模型。基于运动学模型建立机器人全参数几何误差模型,同时在误差模型的基础上,构造机器人的灵敏度模型,并依据各误差源的全局灵敏度系数对误差源进行筛选,筛选出 18 个主要几何误差源,最终通过 MATLAB（Matrix Laboratory）仿真验证误差模型和灵敏度模型的正确性。

最后,将主要几何误差源分为静态误差和动态误差并进行分步补偿。对于静态误差,采用运动学标定的方法进行补偿,即在误差模型的基础上,通过光学三维动作捕捉系统获得测量点实际位姿并使用最小二乘法对误差源进行参数辨识,修正运动学静态几何参数,通过 ADAMS 仿真验证运动学标定方法的可行性；对于动态误差,通过光学三维测量系统以及雷赛控制系统实现动态误差的实时补偿。最终通过实验验证了补偿算法的有效性。

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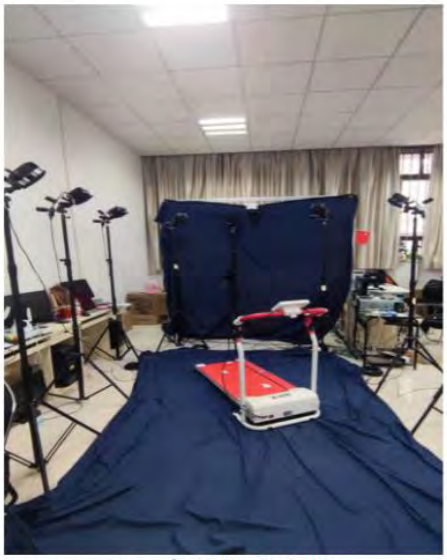

(a) 实验场景布置

(b) 采集人体步态

NOKOV 度量动作捕捉在研究中的应用摘录

本章首先通过光学三维测量系统 NOKOV 采集人正常行走过程中的步态数据， 通过滤波和拟合得到人正常行走过程中步态周期轨迹，优化得出索驱动下肢康复机器人的一组配置。基于该配置，计算出机器人的力旋量可行性工作空间，并验证了步态轨迹的可行性。采用 D-H 法和矢量封闭原理建立索驱动下肢康复机器人的运动学模型。最后使用 CASPR 软件仿真验证了该机器人运动学模型的正确性，为后续的误差分析和补偿提供了数学基础。

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踏板式下肢康复机器人的设计与研究

关键词

下肢康复机器人；三维运动捕捉；步态轨迹建模；运动学分析；运动控制

摘要

如今因为脑卒中、脑外伤以及脊柱损伤等原因造成的下肢功能障碍患者逐年增多，科学研究表明人体中枢神经系统具有一定可塑性，患者通过科学合理的主动或者被动训练，肢体机能可以得到修复，从而降低致残率，保障患者术后生活质量。传统康复训练以人工辅助为主，训练的精度和强度难以保证。下肢康复机器人可以根据患者的病情程度，提供不同的训练模式，取代康复医师繁重的体力劳动，为康复医师提供客观准确的运动数据，方便其为患者做康复指导，从而保证训练的强度和精度，提高康复效率，使得患者更早的回归家庭，回归社会。下肢康复机器人的核心功能是模拟人体下肢步行动作，辅助患者进行康复训练。通过对国内外康复机器人进行对比分析，根据人体下肢运动机理，本文设计了一款踏板式下肢康复机器人，主要研究内容如下：（1）标准步态轨迹的获取和分析。对下肢运动机理和步态周期过程进行了详细分析，用光学式三维运动运动捕捉设备对正常人平地行走、上坡、下坡时的运动轨迹进行数据采集，对采集到的离散数据点进行筛选，然后拟合出标准步态轨迹模型。（2）下肢康复机器人的结构设计和分析。在满足患者康复训练需求且保证安全的前提下，本文设计了一款具有 6 自由度的踏板式下肢康复机器人，其主要由控制主机、减重机构、踏板机构三部分组成。文章对踏板机构驱动电机的选型进行了详细分析。运用 Adams 软件进行仿真分析，验证了机构尺寸的合理性。对康复机器人进行了正、逆运动学分析，运用 Solidworks 软件绘制了机构装配图，同时完成了样机的制作。（3）下肢康复机器人运动控制策略的选取和分析。根据患者病情程度的不同，在患者康复训练初期采取独立 PD 控制策略，在康复训练中后期采用独立 PD+重力补偿控制策略，在 Simulink 建立控制模型进行仿真分析，对康复机器人结构设计的合理性和控制策略的可行性进行了验证。

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（a）采集设备　　(b)辅助平台

图 2-6 数据采集设备

Fig.2-6 Data acquisition equipment

NOKOV 度量动作捕捉在研究中的应用摘录

本实验采用北京度量科技有限公司提供的 Nokov 数字式光学捕捉设备进行人体数据的采集。该套设备在 3m×3m 平地区域四周架设有 8 个 Mars2H 系列红外摄像头，另外在采集者下肢关键节点粘贴反光 Marker 点，采集者运动范围处于相机视野交集部分，当采集者在场内运动时，相机便可以 340HZ 的频率进行连续拍摄，然后将采集数据传输到处理终端，通过软件对点云数据进行处理，将具体的运动轨迹赋予到人体骨骼上，从而完成下肢运动数据采集工作。为采集人体平地行走，上下楼梯的运动数据，本实验专门制做了坡台、简易梯台，同时购买了一台小米跑步机，实验平台和辅助器材如图 2-6 所示

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无动力 TKA 术后康复训练装置设计与实验研究

关键词

TKA 术后康复辅具；动力学分析；动作捕捉实验；肌电测试

摘要

随着康复医学逐渐兴起,人工全膝置换(Tord knee arthroplasty,TKA)术后的康复训练受到了人们的重视,康复辅具的研制也因此受到国内外研究者的关注。无动力 TKA 术后康复辅具能够有效帮助患者恢复关节功能,纠正术前与术后可能存在的功能问题。本文在对人体下肢步态规律研究的基础上,设计了一种针对 TKA 术后肌力训练的无动力下肢康复辅具,对辅具结构/机构进行创新设计,并对其可行性进行实验研究。本文主要研究内容如下:(1)TKA 术后康复训练步态数据利用动作捕捉系统对受试者步态数据进行采集,在 Seeker 软件中对数据进行后处理,获得人体下肢髋、膝关节角度变化,将关节角度数据输入 Matlab 得到关节力矩。(2)无动力康复辅具结构设计。以矢状面人体下肢步态数据为依据,并结合 TKA 术后康复需求,对辅具结构设计提出要求。辅具整体结构由腿部连杆、关节传动机构以及阻尼机构等组成,能够满足患者在步行与坐卧姿态两种模式下的下肢功能和肌力训练,在确定设计方案后,对模型关键零件进行有限元分析,验证零件设计的合理性。(3)康复辅具动力学分析。利用拉格朗日方程建立了下肢动力学模型,对 TKA 术后康复辅具进行动力学分析。利用 Matlab 进行了数值模拟计算,并与 Adams 软件动力学仿真结果进行了对比,仿真结果验证了所建立动力学模型的正确性。最后,在 Adams 软件中对穿戴辅具前后髋、膝关节仿真力矩进行了对比,初步验证了康复辅具的可行性。(4)康复辅具实验验证。在理论支撑的基础上,对康复辅具的可行性进行实验验证,分析获得的实验数据,对比穿戴辅具前后的髋、膝关节力矩和下肢股四头肌与腘绳肌表面肌电信号变化,最终验证康复辅具的可行性。本文将理论与实验相结合,分析了穿戴辅具前后下肢部分肌肉的表面肌电信号变化以及下肢关节力矩变化,验证了设计方案的可行性,研究成果为此类型康复辅具设计提供了理论借鉴。

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NOKOV 度量动作捕捉在研究中的应用摘录

步态分析是对人体运动规律的研究分析，在运动生物力学中，它用于帮助人群更有效地行走，并识别受伤者的姿势或运动相关问题，获取人体下肢运动的数据信息，从而在康复装置的设计中提供动力学模型所需要的参数信息。本文通过 NOKOV 度量光学三维动作捕捉系统进行实验，利用摄像头对实验者步态动作进行捕捉，通过 Seeker 软件分析得到下肢运动角度等信息。光学式动作捕捉系统获取数据时依靠光学摄像机，通常采集过程中需要 8 个摄像机，并且按照环形或者左右两行排列，在中间区域人体完成实验动作，利用摄像头对人体动作进行捕捉，完成实验数据采集。

引用格式 霍东锋. 无动力 TKA 术后康复训练装置设计与实验研究[D].西安理工大学,2023.DOI:10.27398/d.cnki.gxalu.2023.001339.

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膝关节假体个性化设计与接触力学研究

关键词

膝关节置换；Hertz 接触理论；全膝关节建模；假体设计；有限元仿真模拟

摘要

关节置换是治疗晚期膝关节骨性关节炎患者最有效的方式之一，但是目前膝关节假体类型较为单一，难以满足不同患者的使用需求。针对上述问题，本文基于人体全膝关节模型重建,完成膝关节假体个性化设计，并进行接触力学分析与验证。主要研究内容包括:

(1)膝关节生物力学分析。介绍人体膝关节的生理结构与运动规律；基于 D-H 法构建人体下肢运动学模型和膝关节力学模型；推导膝关节假体组件间的接触应力计算公式，用于后续有限元仿真结果的验证。

(2)人体正常步态实验数据采集与分析。运用动作捕捉系统和足压测试系统采集被试步态数据，获取一个完整的步态行走周期内下肢运动学和运动学参数:、；借助 Opensim 仿真软件，获得膝关节受力和力矩数据结果，为后文有限元仿真模拟提供数据支撑。

(3)人体全膝关节模型构建和膝关节假体 3D 重构。基于被试者左膝关节 MRI 扫描数据，分别利用 MIMICS、Geomagic Studio 等软件进行人体膝关节模型重建、表面处理以及组件装配;基于人体全膝关节模型，提取膝关节模型的轮廓曲线特征，利用 SolidWork 等软件对膝关节假体各部分进行 3D 建模、表面处理以及模型实体化。

(4)全膝关节模型和置换后假体模型的有限元仿真模拟与验证。对建立的膝关节模型和假体模型进行材料赋值、网格划分等前处理，利用有限元仿真软件 Abagus 对其模拟仿真，对仿真结果进行分析与总结；最后利用接触力学公式计算膝关节假体部件之间的理论接触应力，并与仿真结果进行对比验证。

综上，本文提出一种从全膝关节模型重建到膝关节假体个性化设计的整套流程与方法，构建多组人体全膝关节模型和膝关节假体模型，对其接触力学进行研究，并将仿真结果与已有研究数据对比，验证所设计的个性化膝关节假体的有效性。该方法对解决目前患者由于膝关节假体不匹配所带来的关节疼痛问题具有重要意义。

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图 3-1 整体设备图
Fig.3-1 Overall equipment drawing

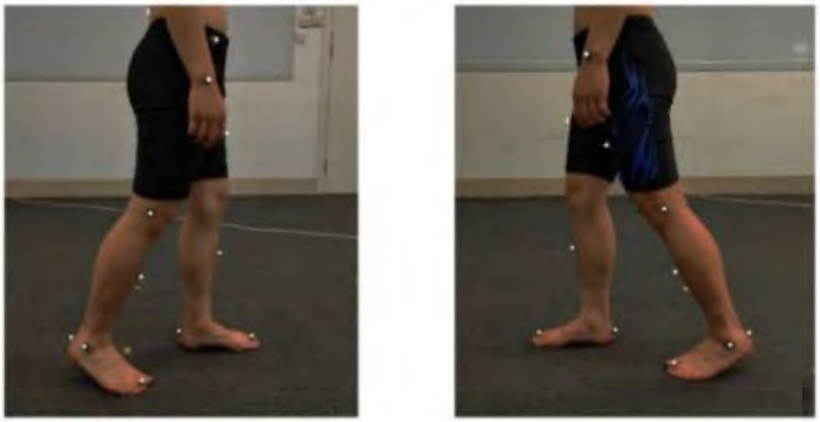

图 3-5 受试者实验过程
Fig.3-5 Subject test procedure

NOKOV 度量动作捕捉在研究中的应用摘录

本套实验室 NOKOV 光学动作捕捉系统的数据采集更加准确、更加迅速、更加稳定，而且可以实现实时运动捕捉。利用 NOKOV 动作捕捉系统识别被试者身上的标记点后建立受试者的静止人体骨架模型，后续实验对人体下肢运动学研究都是基于该静止人体骨架模型。

引用格式 郭雨.膝关节假体个性化设计与接触力学研究[D].西安理工大学，2024.DOI：10.27398/d.cnki.gxalu.2024.000587.

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膝踝关节外骨骼人机匹配性设计与优化研究

关键词

膝踝关节；膝关节瞬心；助力外骨骼；人机耦合仿真分析；实验验证

摘要

为了解决现有外骨骼与人体腿部协调性的问题，设计一种基于人机匹配性的膝踝关节外骨 骼，实现了人体在运动过程中具有高适应性的同时提供运动助力。通过动作捕捉系统采集了下肢关节 运动时空数据，结合生理膝关节滚滑运动特性，设计了能够适应人体膝关节运动瞬心的"J"字型运动 轨迹的四杆机构，提出了模拟膝关节运动的连杆机构优化设计方法，通过数值模拟验证了优化后四杆 机构能够很好的贴合人体运动，并结合角度传感器实现助力外骨骼控制系统的开发，进而借助步态和 肌电实验对助力外骨骼性能有效性进行验证。实验结果表明，穿戴后膝关节角度峰值变化幅度小于 5%， 膝关节力矩减小，股外侧肌、腓肠肌、股二头长头肌等肌肉活动度下降。

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图 24　志愿者未穿戴外骨骼状态

Fig.24 Volunteers without wearing exoskeletons

NOKOV 度量动作捕捉在研究中的应用摘录

为了检验运动学模型的准确性，明确下肢的关节角度、空间轨迹和关节力矩等步态参数，为下肢外骨骼设计提供必要的数据支撑，需要在正常行走条件下记录步态数据。使用 NOKOV 动作捕捉系统能够记录志愿者下肢运动时的运动状态，计算关节运动角度等步态数据，为后续的研究提供依据。

引用格式 唐欣尧,殷榕,王旭鹏,等.膝踝关节外骨骼人机匹配性设计与优化研究[J/OL].中国机械工程,1-11[2025-09-16].https://link.cnki.net/urlid/42.1294.TH.20250113.1134.002.

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下肢康复机器人结构设计与建模分析

关键词

康复设备；有限元静力分析；六连杆路径综合；运动学分析；PID 控制算法

摘要

针对运动功能损伤患者,采用康复机器人进行康复训练是一种有效的替代方案。相对于人工康复治疗,康复机器人具有更高的运动精度和更强的承载能力,更适合于高重复性的康复训练。本文基于斯蒂芬森Ⅲ六连杆综合技术,设计了单电机驱动的康复机器人,可通过该机器人帮助患者达到恢复正常步态的目的。主要做了以下研究工作:(1)探讨利用六杆联动综合理论,设计具备自然行走运动的单自由度下肢康复机械腿的机构。首先通过对人体下肢结构和运动机理的分析,构建 3R 链结构,其次,借助连杆综合数学理论,依据 Nokov Mars2H 三维步态分析系统采集 250 个数据点,最后使用 B 样条进行拟合和筛选,绘制踝关节的运动轨迹,基于此,获得一组斯蒂芬森Ⅲ六连杆可行性设计方案。(2)使用 Soidworks 软件设计康复机械腿的三维模型,并使用 ansys-works 软件对康复机械腿的结构进行了有限元静力分析。(3)进行运动学和动力学分析,采用矢量闭环方程推导出康复机械腿系统的运动学方程,分别使用 Solid Works Motion 和 MATLAB 软件对腿部连杆进行运动学仿真,验证运动学方程的正确性,使用拉格朗日法对本文设计的康复机械腿结构进行动力学分析,获得驱动轴的输入力矩。(4)针对下肢康复机器人的控制需求,设计控制系统,编写控制软件,采用 PID 控制算法并在实物样机进行试验,仿真和试验结果对比,验证控制系统的效果,同时,也验证所设计的下肢康复机械腿可以满足患者以正常人体步态进行康复训练的要求。

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图 2-15 Nokov Mars2H 三维步态分析系统

NOKOV 度量动作捕捉在研究中的应用摘录

运用 Nokov ars2H 三维步态分析系统，对健康人群行走时的运动进行了数据采集，共采集了 250 个点。为了收集对应的运动部位的捕捉数据，标记安装在脚踝处。该系统还可以提供关于步态的运动轨迹、运动速度和运动幅度等信息，从而更全面地了解人体运动状态和行走模式。

引用格式 陈国梁. 下肢康复机器人结构设计与建模分析[D]. 长春工业大学,2023.DOI:10.27805/d.cnki.gccgy.2023.000997.

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虚拟现实技术在柔性上肢康复机器人中的应用

关键词

柔性康复；主被动训练；交互设计；碰撞检测

摘要

根据末端牵引式和外骨骼式上肢康复机器人的特性,研制了一种新型的柔性上肢康复机器人。机器人的康复训练系统结合了主动和被动模式的要素,将虚拟现实（VR）技术引入上肢康复机器人,通过现实环境中的光学 3D 位置捕获以及 VR 环境中的 3D 位置感知,设计了虚拟动态模型交互性节点和碰撞检测实验,实现虚拟现实交互,提高虚拟模型运动实时效果和上肢康复训练精度。VR 和新颖的康复机器人的集成为具有特定任务的患者提供了有效的训练。

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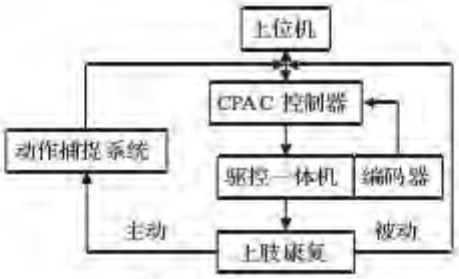

图 5　康复机器人系统原理图

NOKOV 度量动作捕捉在研究中的应用摘录

2.3 柔性上肢康复机器人运动方案
结合柔性上肢康复机器人本体结构，实验室设计了基于虚拟现实技术的柔性上肢康复机器人控制系统，如图 5 所示。控制系统主要由 CPAC 控制器、虚拟现实交互环境、 Nokov 动作捕捉系统等辅助训练设备构成。该控制系统模式含有主被动两套训练方式。被动式康复训练模式是在患者上肢未完全丧失功能，具备一定的自主运动能力下进行的一种模式，该模式简单有效，当前
多数上肢康复机器人都能实现这种训练模式。基于被动康复训练模式，利用辅助设备开发了一种主动式康复训练，即实时监测上肢运动情况，机器人自主带动患者进行康复训练。
利用大量的患者上肢康复过程中训练数据，拟定适合患者上肢运动的速度是 V0。柔性上肢康复机器人进行主动康复训练，通过 NOKOV 动作捕捉系统实时测量上肢在运动空间的位置变化参数。在 CPAC 控制器里，计算动作捕捉系统中每一帧的空间坐标变化量(V)，并且与拟定的速度(V0)进行比较。当测得患者上肢运动速度 V\<V0 时，表示患者自主运动能力不足，需要在康复机器人的牵引下进行运动训练，因此，CPAC 控制发出脉冲信号，驱动末端执行机构，使得绳索牵引上肢运动。当上肢运动速度 V≥V0 时，表示患者能够自主运动，故末端执行机构跟随上肢，做主动运动。当获取上肢运动空间坐标位置后，利用 Unity3D 软件的 SDK 数据插件读取空间坐标位置并转化为虚拟动态模型节点坐标系，实现虚拟现实运动交互。

引用格式 杜豪,杨岩,张成杰.虚拟现实技术在柔性上肢康复机器人中的应用[J].计算机工程与应用,2020,56(24):260-265.

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压力相似度模型的人体侧翻状态估计

关键词

分析力学；压力特征；余弦相似度；压疮预防；行为分析

摘要

侧翻是失能人群护理的重要环节，由装置自主执行侧翻流程已成为无人护理发展的重要任务之一。为提升侧翻类装置的安全性与智能性，以人体侧翻过程中必然会产生的压力信息作为核心指标，构建相关模型估计人体侧翻状态并指导控制系统执行。采用分析力学由人体侧翻过程中肩部与臀部七个压力点构造矩阵函数，依据解剖学原理将身高与体重作为可变参数，实现模型的主动适应。通过余弦相似度与皮尔逊相关系数共同评估实际压力与理论压力，最小相似度能够达到0.8269，提升模型抗干扰能力，实现人体侧翻状态的估计。构建的人体侧翻状态估计模型进一步分析了失能人群的侧翻动作，对康复辅具智能化、健康状态评估以及居家常态化照护等方面具有重要意义。

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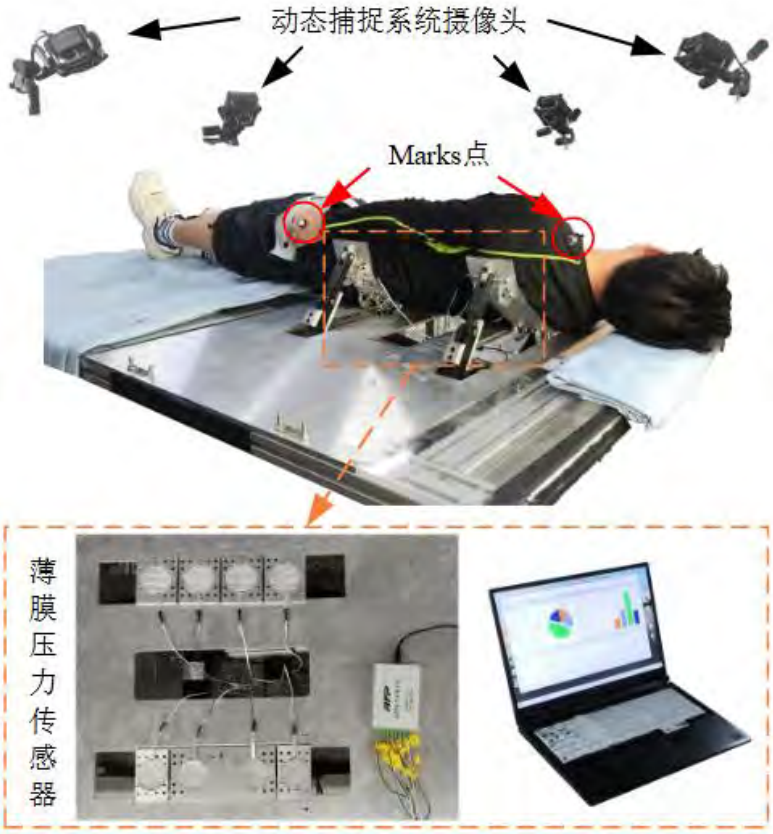

图 4 人体侧翻角度及压力数据采集试验台

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采用 MD30-60 薄膜压力传感器与 NOKOV 动态捕捉系统共同搭建侧翻力检测与侧翻异常模拟实验，模拟真实侧翻情况下的七个实际力，并按照力合成关系将其合成为侧翻力矩阵函数中的求解力。薄膜压力传感器的量程为 0\~50kg，采样频率为 10Hz。动态捕捉系统的摄像头具有 1200 万像素的分辨率，镜头频率达到 240Fps/Hz。将动态捕捉系统的反光点分别粘贴在志愿者的头部、肩膀、手部以及腰部等位置，采用六个摄像头捕捉志愿者身上的反光点位置，分析人体侧翻角度。

引用格式 孙超越,潘国新,刘甜,等.压力相似度模型的人体侧翻状态估计[J/OL].电子测量技术,1-9[2025-09-16].https://link.cnki.net/urlid/11.2175.TN.20250613.0930.006.

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用于增强现实头部外科手术导航的无标记配准方法

关键词

手术导航；增强现实；三维配准；HoloLens

摘要

传统头部手术导航系统通常使用双目红外相机跟踪固定在人体表面的逆反射标记，实现术中导航的配准定位。标记需要手动安装，配准精度易受到标记安装精度的影响，且存在准备时间长，易对病人造成侵入式损伤的问题。导航系统使用屏幕交互，医生需要在手术部位和屏幕之间反复切换视线，可视化效果不直观，且加重了医生的认知负担。为了解决上述问题，提出了一种使用结构光相机的无标记配准方法，将三维影像数据和人体目标部位空间配准。使用结构光相机得到患者面部点云，然后通过一个包含粗配准和精配准算法的快速精确的配准管线得到患者头部的精确位姿。将该配准方法与光学透视头戴式显示器结合，搭建了一个增强现实配准系统。通过多用户实验验证了本文配准方法和功能的有效性。实验结果显示，目标配准误差的平均精度为（2.61 ±0.55） mm，真实和虚拟模型的重叠系数为 0.9548，配准算法所需时间平均约为 0.47 s。测试结果表明，该系统可以快速准确地自动配准，能够为医生在手术导航中提供准确的目标空间信息，满足头部手术导航的精度和时间要求，有进一步发展完善并应用到临床的潜力。

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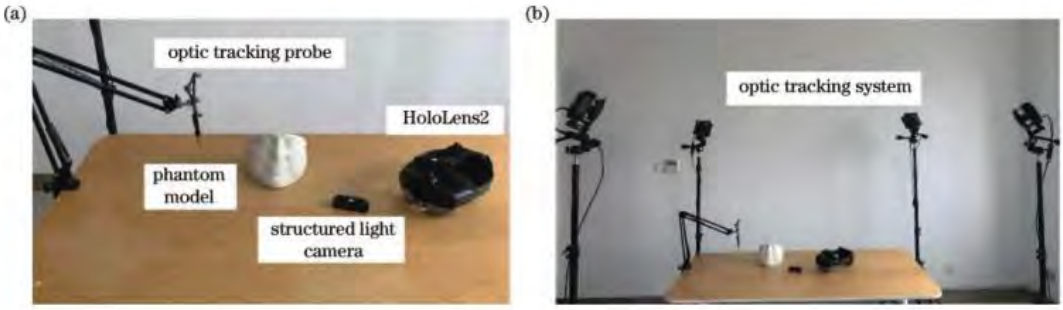

图6 实验设置。(a)操作平台;(b)光学跟踪系统

Fig. 6 Experimental setup. (a) Operation platform; (b) optical tracking system

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实验中使用 Unity 3D（Unity Technologies， version 2021 .3.31）为 HoloLens2 构建 Windows 通用应用平台（UWP）交互程序，使用 MRTK（MR tookit）的版本为 v2.8.2.0。点云配准使用 Open3D 库。
使用一套由 4 个红外相机组成的高性能光学动作捕捉设备（Nokov Mars1.3H）来验证本文方法的配准精度。这套动作捕捉设备可以主动发射 800 nm 波长的红外光并跟踪反射该红外光的逆反射标记球。动作捕捉系统的跟踪精度可以达到亚毫米精度，能够满足实验的精度要求。利用该系统跟踪有 4 个非共线逆反射标记球的探针，使用该探针获取空间中标记点的空间位置坐标。实验设备如图 6 所示。

引用格式 陈旭竞,许春晓,李洋,等.用于增强现实头部外科手术导航的无标记配准方法[J].激光与光电子学进展,2024,61(20):281-290.

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肘关节康复机器人机构设计及应用研究

关键词

肘关节；康复训练机器人；混联机构设计；Anybody 仿真分析

摘要

肘关节康复训练机器人相对于传统医师医疗手段在帮助瘫痪病人进行单关节康复训练运动时具有训练效率高、可重复性强等优点。本文在综述现有肘关节康复训练机器人所存在问题的基础上，结合肘关节康复训练的基本要求，研究了肘关节康复训练机器人的机构设计、工作空间优化以及人机仿真分析等内容。论文工作内容如下：

1.详细分析了肘关节的生理参数、运动机理和关节转动中心特性，为接下来的机构设计和人机仿真分析奠定了基础；借助光学三维动作捕捉系统采集了肘关节的真实运动轨迹数据，并以此为基础划分了肘关节不同的运动周期和拟合了肘关节运动轨迹曲线，为接下来的人机仿真分析奠定了基础。

2.针对现有肘关节康复机器人所存在的设计问题和肘关节康复训练的需求，设计了一种可实现肘关节二自由度康复训练运动的(2-PRR-S)R-PRCR 并联机器人机构和可固定前臂位置的支撑装置机构；使用旋量理论验证了并联机器人机构的自由度特性。利用空间几何分析法推导出并联机器人机构位置逆解与位置正解表达式，进而给出了并联机器人机构的雅克比矩阵，然后结合雅克比矩阵分析了该机构的奇异位形，结果表明：所设计的并联驱动装置机构可实现相互正交的二自由度旋转运动。

3.根据并联机构的奇异位形，确定了并联机构的约束条件，并分析了并联机构的工作空间，然后以最大化工作空间为优化目标，借助遗传算法对并联机构进行了尺度优化；针对人机耦合运动过程中的轴心不匹配和并联机构有限工作空间的问题，设计了一款可有效提高人机耦合运动相容性的双摇杆机构，并在机构基础上进行了运动学分析，最后借助 Solidworks 软件建立混联康复训练机器人的整机模型。结果表明：所设计的混联康复训练机器人能满足肘关节康复训练过程中的工作空间要求。

4.借助 Anybody 生物力学软件进行人机耦合建模与分析。以肘关节运动轨迹数据所拟合的方程作为机器人运动的驱动函数，对比分析了肘关节原动肌在人机耦合运动过程中的生理参数差异性，在保证康复训练安全性的前提下优化了康复训练方案。

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2.3.1 运动捕捉实验
本文所采用的运动捕捉实验设备是基于光学反射原理的，即通过在捕捉对象贴附反光点，借助摄像镜头捕捉反射光，进而获取捕捉对象运动状态的方法，具有较高的精确性和简便性。
本次实验使用北京度量科技有限公司最新研发的 Nokov 光学三维动作捕捉系统，配备七台高精度的红外摄像头、一台信息转换器和一台计算机，所配备的操作分析系统支持操作系统进行系统标定、校正、数据采集和导出数据等功能。通过捕捉人体上肢运动过程中姿态信息的变化，构建相机所采集到反光点的三维运动数据。

引用格式 李博超.肘关节康复机器人机构设计及应用研究[D].天津大学，2019.DOI：10.27356/d.cnki.gtjdu.2019.003592.

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基于非线性干扰观测器的下肢康复机器人滑模跟踪控制

关键词

步态数据；Opensim；运动捕捉设备；轨迹跟踪；自适应反演滑模

摘要

【目的】 在现代医疗的发展中，下肢外骨骼康复机器人在脑卒中和脊髓神经损伤等疾病的治疗中有着越来越重要的作用，针对下肢外骨骼康复机器人在康复训练中跟踪效果不稳定和抗外界不确定性干扰能力差等问题，提出来一种基于 Nokov 光学运动捕捉设备与生物力学仿真软件 Opensim 联合仿真分析所得的人体步态数据的非线性干扰观测器的自适应反演滑模控制系统。【方法】 首先，通过 Nokov 光学运动捕捉设备获取健康人体的步态数据作为生物力学仿真软件 Opensim 的数据输入；然后，通过生物力学仿真软件 Opensim 对人体下肢的肌肉骨骼模型进行仿真，获取期望轨迹；最后，将通过生物力学仿真软件 Opensim 获取的期望轨迹输入非线性干扰观测器的自适应反演滑模控制系统，使下肢外骨骼康复机器人的运动轨迹跟踪期望轨迹。通过 Matlab 的仿真结果，验证该方法的有效性。【结果】 实验结果表明：髋关节的角度最大跟踪误差为 0.053 394 rad，膝关节的角度最大跟踪误差为 0.207 75 rad；同时，在进入初始状态后迅速归于稳定，可以合理的满足康复训练需求。【结论】 现在下肢外骨骼康复机器人的种类多种多样，但是实现更稳定、更加精确和抗干扰能力更好的下肢外骨骼康复机器人轨迹跟踪仍然具有非常重要的意义。

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图 2　动作捕捉摄像头的实验场地

Fig.2　The experimental site for motion capture cameras

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本文动作捕捉采集实验的对象是一名身高 172 cm，体重 74 kg 的 26 岁的健康男性。在其髋关节、膝关节和踝关节处的关节中心处，分别贴上专用的反光标记 Maker 点。使其在规划好的实验空间内进行正常的匀速步态行走。通过 Nokov 三维动作捕捉摄像头采集到的步态数据在采集成功以后，导出为所需要的 c3d 文件形式。c3d 文件通过 Matlab 转换成 Opensim 所需要 trc 文件，trc 文件包含了实验者的实验轨迹数据。在使用 Opensim 的逆运动学功能得到了运动捕捉设备所采集的原始关节角度数据。根据图 1 的三维图形所示，可选取单腿作为控制对象。

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一种新型多功能护理轮椅机器人结构设计与研究

关键词

多功能护理轮椅机器人；姿态变换;膝关节补偿；如厕对接;动作捕捉实验；

摘要

针对肢体功能障碍老年人在居家养老中面临的诸多挑战，提出了一种新型多功能护理轮椅机器人-M-nur，旨在满足老年人居家养老中的护理辅助需求。M-nur 集成了全向移动、多姿态变换、如厕对接及洗浴辅助等功能。为解决姿态变换过程中膝关节的相对滑移问题，设计了一种主动补偿的姿态变换连杆结构，并通过最小化矢状面面积优化函数确定了关键连杆的尺寸。针对如厕模块，设计了可复位如厕板结构，最大化减少占用空间，并优化了连杆长度，同时进行了复位弹簧受力的动力学建模。进一步对姿态变换结构进行了运动学建模，并通过 Adams 仿真分析了膝关节相对滑移补偿效果。通过实际样机的动作捕捉实验，验证了主动补偿机制的实机效果。实验结果表明，M-nur 能够有效补偿姿态变化过程中的膝关节相对滑移，并且站立过程中的补偿效果优于躺卧过程。此外，还进行了样机的便器对接使用实验，并通过编码器对如厕升降过程进行了采集分析，结果表明，M-nur 能够良好适配座高在 502 mm 以下的便器。最后，邀请老人对 M-nur 与同类产品进行对比体验，结果表明，M-nur 虽然功能良好，但背垫需要更换为更光滑的皮革，安全绑带应结合刚性护栏，以提高使用安全性。

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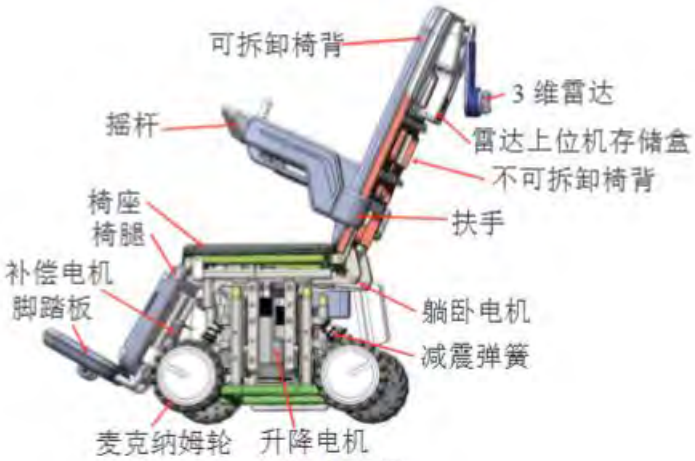

(a) 侧视图

(b) 后视图

图 1　M-nur 的整体结构

Fig.1　The overall structure of M-nur

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3.2 位姿变换滑移补偿实验
*通过 **NOKOV 动作捕捉系统**，对样机的三姿态变换模块中人体膝关节的补偿效果进行 Marker 点轨迹捕捉测试。测试前，首先利用如图 24(b) 所示的 L 架定义空间 3 维笛卡儿坐标系的方向和原点；随后，借助 T 架的挥动在电脑配套软件中定义摄像头捕捉的 3 维空间范围。如图 24(a) 所示实验过程中，在身高分别为 1.73 和 1.68 m 的测试人员的腿部侧面膝关节区域粘贴一个 Marker 点，以进行后续的空间位置捕捉。图中黑色坐标系为电脑动作捕捉系统中定义的实际坐标方向。*

引用格式 杜妍辰,吴承稼,喻洪流.一种新型多功能护理轮椅机器人结构设计与研究[J].机器人,2026,48(02):312-324.DOI:10.13973/j.cnki.robot.240362.

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基于肩肱节律的高人机相容上肢外骨骼康复训练控制方法

关键词

上肢外骨骼;肩肱节律;康复训练;人机相容性

摘要

上肢康复外骨骼是解决脑卒中上肢运动障碍康复需求的重要方案，但其运动控制方法如何适配肩肱节律以匹配人体上肢的自然运动，仍是关键难题。采用已搭建的双侧上肢康复外骨骼系统，单侧包含 10 个主动旋转自由度与 2 个被动移动自由度，提出了基于肩肱节律的肩关节协同运动控制方法。首先，建立了重力补偿下的外骨骼零力运动与轨迹跟踪控制方法；然后，通过构建肩关节旋转中心与大臂姿态的映射模型，并进一步结合逆运动学解析，实现了外骨骼运动与人体肩肱节律下肩关节旋转中心变化的匹配。实验结果显示，相比外骨骼肩锁关节锁定状态，其肩锁关节节律性运动下的肩关节外展/内收角度更趋近人体的自然运动状态，斜方肌、三角肌等关键肌肉激活度显著降低，且肌肉部位间的相对激活状态比值更趋近于人体不穿戴外骨骼时的基线状态。这表明所提出的基于肩肱节律的上肢康复控制方法，可有效契合人体肩部生理运动规律，进而提高外骨骼辅助下人体康复训练的人机相容性。

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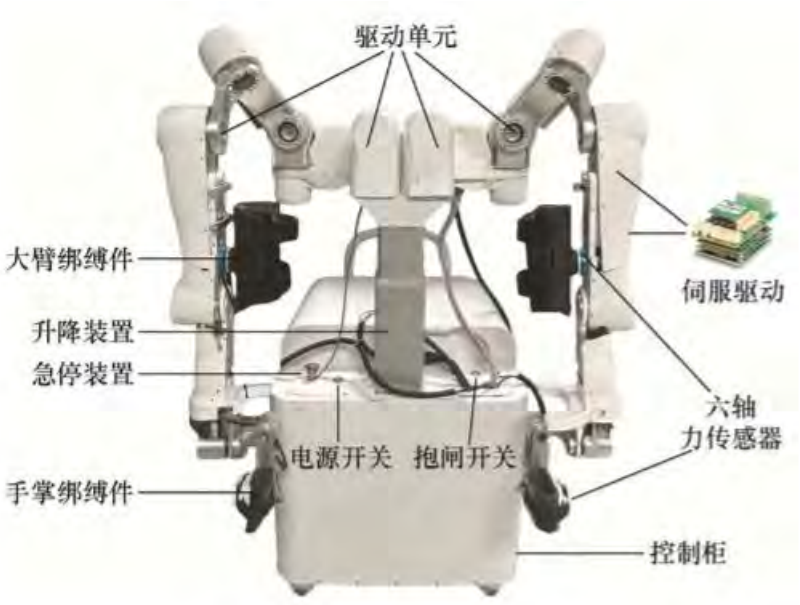

图 8　机器人系统实物图

NOKOV 度量动作捕捉在研究中的应用摘录

3.2 实验步骤\n1. 传感器布置：机器人关节运动学数据通过内置在伺服电机中的绝对值编码器以 200 Hz 的频率采集；人体运动学数据通过 8 个 NOKOV 的相机组成动作捕捉系统采集，标记点布置方案如图 8 所示，采集频率是 90 Hz；人机交互力矩是通过 6 维力传感器同样以 200 Hz 的频率记录；为评估人体生理学数据，以肌肉激活程度为指标，采用 Delsys Trigno Centro 系统(美国 Delsys Incorporated 公司)采集表面肌电(Surface electromyography, sEMG)信号，采样频率为 2148 Hz。图 9 展示了 sEMG 传感器的布置方案：以成对方式贴附于 4 块关键肌肉，分别为斜方肌(Trapezius descendens, TD)、三角肌中部(Medial meltoid, MD)、三角肌前部(Anterior deltoid, AD)及三角肌后部(Posterior deltoid, PD)。传感器布置遵循欧洲表面肌电信号标准化建议(SENIAM)指南，目标是评估上肢肌肉激活状态。

引用格式 李辉,田哲豪,焦然,等.基于肩肱节律的高人机相容上肢外骨骼康复训练控制方法[J/OL].机械工程学报,1-11[2026-06-09].https://link.cnki.net/urlid/11.2187.TH.20260527.0858.012.

链接

https://kns.cnki.net/kcms2/article/abstract?v=7jvqSXIa2LW5KsLkOtBlRVmqfaskvpDM6cMFDRUF9ZRiGrTy2kbBbjjZjI70tSY5uZEBDYKznABuqcDeLCCa6E0vfiE3sAlcwJ78HpiaiX2y5p1PbvTLRvGrt2x3pvn1irRWcctCzGn4PIA3FNvCs-yr9kdeGIQOShsSFPpVQkQ=&uniplatform=NZKPT

VII. Exoskeleton/Wearables

A Closed-loop Control for Lower Limb Exoskeleton Considering Overall Deformations: A Simple and Direct Application Method

Keywords

Legged locomotion, Limbs, Deformation, Exoskeletons, Dynamics, Estimation, Sensors, Intelligent robots, Foot

Abstract

In this paper, considering overall deformations of the exoskeleton, we couple deformations relationship network (DRN) with fractional order viscoelastic (FOV) controller, proposing a novel DRN-FOV closed-loop control method, endowing exoskeleton with stable dynamic walking ability. Simply by utilizing only the data from the 6-axis force/torque sensors, the DRN can directly capture the mapping relationship between the foot reaction force/torque of the exoskeleton and its overall deformations. We introduce the FOV to eliminate disturbances and stabilize during walking tasks. The closed-loop control method directly compensates for the overall deformations of the exoskeleton and enables the wearer to walk stably wearing the exoskeleton. To assess the effectiveness of the proposed control method, walking tasks were effectively carried out on subjects with varying body parameters using the developed exoskeleton. The experimental results show that the DRN-FOV closed-loop control method accurately estimates and compensates for deformations, resulting in an improved dynamic walking ability of the exoskeleton with wearers.

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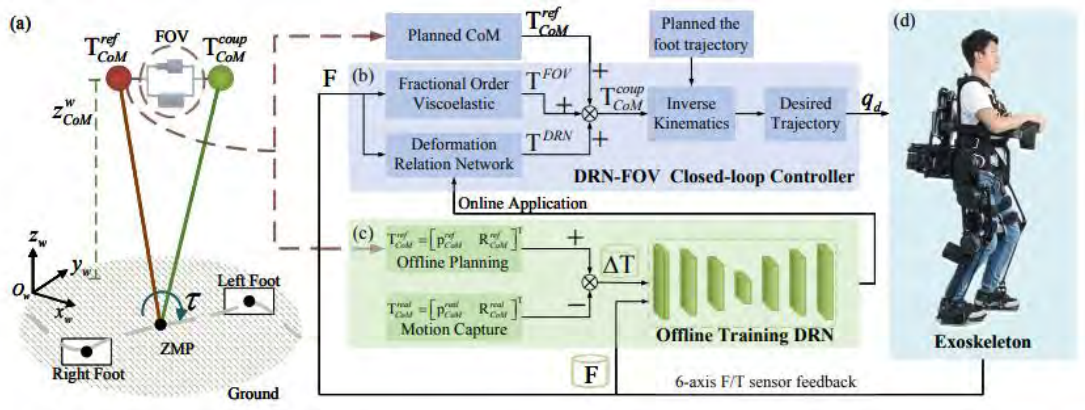

Fig. 3. The proposed comprehensive framework for closed-loop control consists of: (a) Exoskeleton dynamics model based on a linear inverted pendulum. (b) The proposed DRN-FOV closed-loop controller. (c) The offline training of the DRN. (d) The exoskeleton system

How NOKOV Contributes to the Research

As shown in Fig. 3(c), the training data for the DRN model was collected using the NOKOV motion capture system, and our previous work details the data acquisition process [32]. The model is built on the PyTorch platform, and a GeForce RTX 3070 Ti GPU is used to train the model.

Citation Li F, Yang M, Chen Z, et al. A Closed-loop Control for Lower Limb Exoskeleton Considering Overall Deformations: A Simple and Direct Application Method[C]//2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2024: 13626-13633.

Link https://ieeexplore.ieee.org/abstract/document/10801977

A Dual-Mode, Scalable, Machine-Learning-Enhanced Wearable Sensing System for Synergetic Muscular Activity Monitoring

Keywords

bimodal sensing, electromyography, force myography matrix, iontronic sensor, lower-extremity wearable system

Abstract

Simultaneously detecting muscular deformation and biopotential signals provides comprehensive insights of the muscle activity. However, the substantial size and weight of detecting equipment result in reduced wearer benefits and comfort. It remains a challenge to establish a flexible and lightweight wearable system for mapping muscular morphological parameters while collecting biopotentials. Herein, a fully integrated dual-mode wearable system for monitoring lower-extremity muscular activity is introduced. The system utilizes an iontronic pressure sensing matrix (16 channels) for precise mapping of force myography (FMG) within a single muscle, while simultaneously capturing the muscular electrophysiological signals using a self-customized electromyography (EMG) sensing module. Experimental results show that the bimodal sensing system is capable of capturing complementary and comprehensive aspects of muscular activity, which reflect activation and architectural changes of the muscle. By leveraging machine learning techniques, the integrated system significantly ($p < 0.05$) enhances the average gait phase recognition accuracy to 96.35%, and reduces the average ankle joint angle estimation error to 1.44°. This work establishes a foundation for lightweight and bimodal muscular sensing front-ends, which is promising in applications of human–machine interfaces and wearable robotics.

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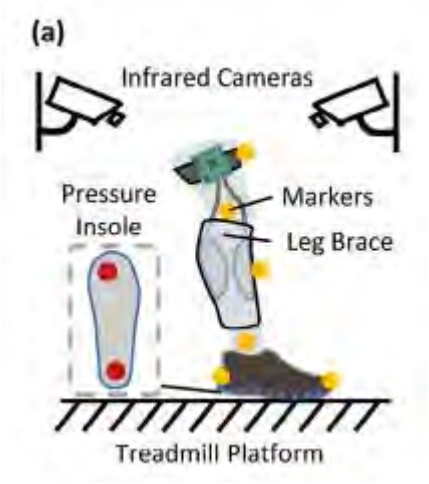

How NOKOV Contributes to the Research

A pressure insole, which was equipped with resistive pressure sensors (effective sensing area: 700 mm^2, measuring range: 0.02–20 kg) at the toe and heel locations, was worn to collect the ground reaction force and divide gait phase during walking. The dynamic walking test was conducted on a treadmill (150/50, h/p/cosmos), with three types of locomotion investigated (level-ground walking, ramp ascending with 5° slope, ramp descending with 5° slope). During each session, the subject walked at the speed of 0.8 m·s^{-1} for ≈2 min, and the data from the middle 1 min were recorded to ensure validness. A motion capture system (NOKOV Science & Technology Co., Ltd.) was used to analyze ankle joint kinematics.

Citation Wang T, Jiang D, Lu Y, et al. A dual-mode, scalable, machine-learning-enhanced wearable sensing system for synergetic muscular activity monitoring[J]. Advanced Materials Technologies, 2025, 10(3): 2400857.

Link https://onlinelibrary.wiley.com/doi/10.1002/admt.202400857

A Hip Active Lower Limb Support Exoskeleton for Load Bearing Sit-To-Stand Transfer

Keywords

Sit-to-stand (STS) transfer · Stand up assistance · Exoskeleton

Abstract

Sit-to-stand (STS) transfer is a basic and important motion function in daily living. Most currently-existing studies focus on movement assistance for patients who lost mobility or have impaired their muscle strength. In this article, a hip-active lower limb support exoskeleton is designed to assist load bearing STS transfer for healthy persons. In order to provide effective assistance, a self-designed quasi-direct drive actuator is adopted to compose the actuation module and a load bearing stand up assistance strategy is designed based on virtual modwhutel control and gravity compensation. Control parameters are optimized in a musculoskeletal simulation environment with kinematic and kinetic data obtained from the wearer. The experimental results show that muscle activation levels of gluteus maximus and semimembranous are reduced with the help from the proposed exoskeleton during load bearing STS transfer.

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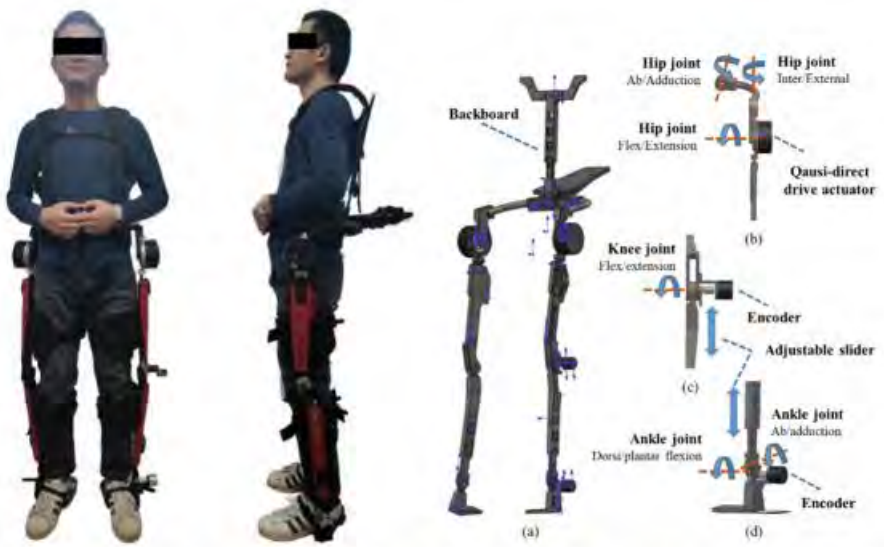

Fig. 1. Front view and side view of Hals-Exo (left column) and the main components of Hals-Exo mechanical system (right column). (a) The overview of assembled Hals-Exo, including two rigied legs and a backboard that supports the load. (b) Front view of the hip joint. The actuator provides torque to assist human STS movement. (c) Front view of the knee joint. The encoder records the bending angle of the knee joint. (d) Side view of the ankle joint.

How NOKOV Contributes to the Research

4 Experiment Setup and Data Process
Because these experiments serve as a proof-of-concept rather than a clinical validation, it is assumed to be sufficient that one subject (male, the age of 26 years, the height of 172 cm and the body mass of 61.5 kg) participated in the experiment. The study was approved by the Wuhan University of Technology Institutional Review Board and informed written consent was obtained for the subject. Subject firstly sat straight on a chair (0.45 m height) with arms cross on chest, knee joint flexed about 100° and hip joint flexed 90°, kept torso as straight as possible. Then he was asked to perform STS movement with preferred speed. The experiment was considered to be ended when subject stood up steadily. The kinematics data were recorded by a passive optical motion capture system (sampling frequency 50 Hz, Nokov, Beijing Metrology Technology Co., Ltd., China) with Helen Hayes Hospital marker setup method. The force and torque data of the feet in three directions during STS movement were obtained from a 6-dimensional force plate (sampling frequency 1000 Hz, BMS400600-1K, AMTI Company, USA). A 16-channel surface Electromyography device (sampling frequency 1000 Hz, ELONXI, China) was used to record muscle activity of gluteus maximus (GM), iliopsoas (IL), rectus femoris (RF), semimembranosus (S) and biceps femoris (BF) to verify the effectiveness of the proposed method.

Citation Zhou J, Zeng Q, Tang B, et al. A hip active lower limb support exoskeleton for load bearing sit-to-stand transfer[C]//International Conference on Intelligent Robotics and Applications. Cham: Springer International Publishing, 2022: 24-35.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:000870561700003

A Multi-IMU System for Assessing Human Walking Dynamics Balance Using the Compass Gait Model

Keywords

Inertial Measurement Unit (IMU), Dynamic Balance Assessment, Wearable Sensors, Compass Gait Model, Human Walking Stability

Abstract

Assessing walking balance is crucial for identifying fall risks in older adults and optimizing rehabilitation strategies for patients with walking impairments. However, current laboratory-based methods for assessing dynamic walking balance are hard to use in daily life scenarios. To address this issue, we proposed a walking balance analysis method based on a self-developed inertial measurement unit (IMU) system consisting of 17 low-cost IMUs. This method collects motion data from key segments of the human body using the IMUs, then uses OpenSim to reconstruct human motion and extract gait parameters, and finally, analyzes walking stability through an improved compass gait model. For validation, we recruited 20 subjects to perform normal and perturbed walking experiments, and the optical motion capture system was used as the reference system. Results indicated that the root mean square error (RMSE) of the gait cycle was 0.158 seconds, and RMSEs of step length and maximum foot clearance were 0.025 m and 0.045 m, respectively. Under normal walking conditions, we calculated the balance indicator, the minimum Euclidean distance, and its RMSE was 0.027. In the perturbed walking experiment, we found that the state point significantly exceeded the balance boundary, then gradually converged and returned to the steady state, showing the effectiveness of the proposed balance stability assessment method. The developed system and the proposed method have the advantages of lightweight design, flexible application scenarios, and low power consumption, which provide a novel technical approach for daily monitoring and assessing walking balance in patients with walking impairments.

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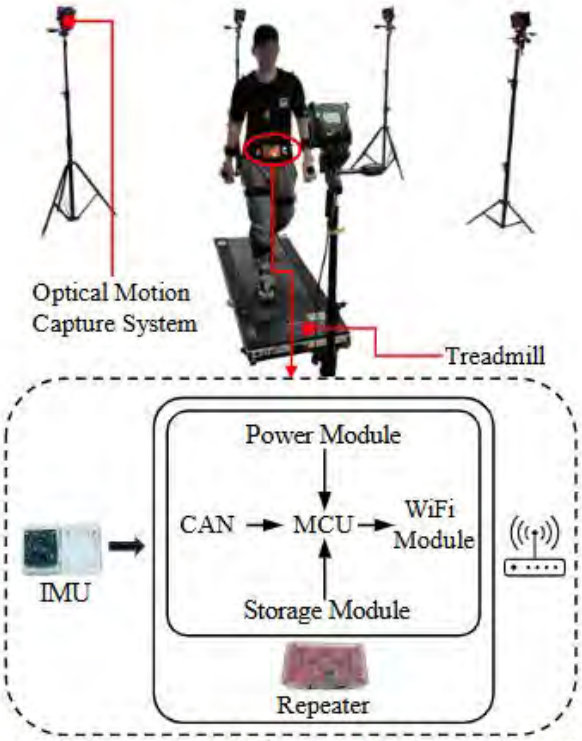

Fig. 6. Experimental setup. Optical motion capture system and IMU system simultaneously collected motion data when subjects walking on a treadmill. The IMUs transmitted data to computers through repeater.

How NOKOV Contributes to the Research

This network connection method effectively alleviated potential overflow when multiple IMUs wirelessly transmitted data. The OMC system consisted of 12 NOKOV motion capture cameras (NOKOV Motion Capture System, Beijing, China) with a sampling frequency of 100 Hz.

Citation Fan B, Zhang L, Wang Z, et al. A Multi-IMU System for Assessing Human Walking Dynamics Balance Using the Compass Gait Model[J]. IEEE Journal of Biomedical and Health Informatics, 2025.

Link https://ieeexplore.ieee.org/document/10974428

A Vector-Based Motion Retargeting Approach for Exoskeletons with Shoulder Girdle Mechanism

Keywords

upper limb exoskeletons; motion retargeting; vector methods; multiple motionrepresentation methods

Abstract

Shoulder girdle plays a dominant role in coordinating the natural movements of the upper arm. Inverse kinematics, optimization, and data-driven approaches are usually used to conduct motion retargeting. However, these methods do not consider shoulder girdle movement. When the kinematic structure of human and that of exoskeletons share a similar joint configuration, analytical motion retargeting methods can be used for exoskeletons with shoulder girdle mechanism. This paper proposes a vector-based analytical motion retargeting approach for exoskeletons with shoulder girdle mechanism. The approach maps the vectors of the upper limb segments to the joint space using vector-based methods. Simulation results using four different motion descriptions confirm the method's accuracy and efficiency.

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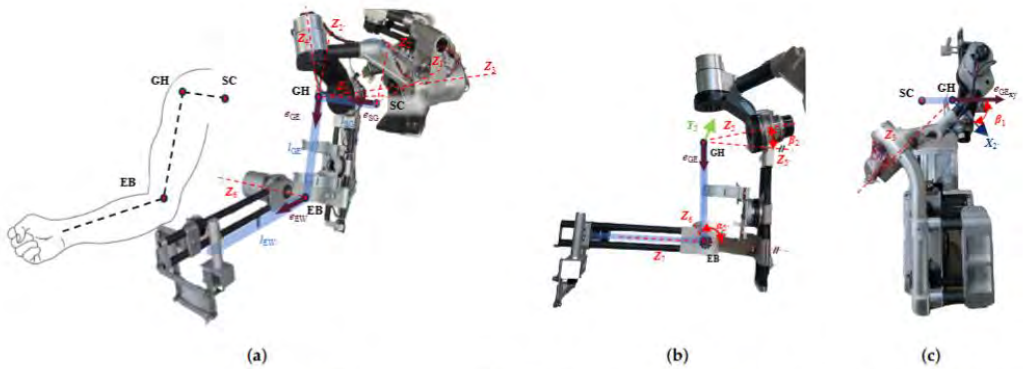

Figure 1. The configuration of FREE II. (**a**) Mapping between human and FREE II. (**b**) Detailed view of upper arm link. (**c**) Top view of FREE II.

How NOKOV Contributes to the Research

5\. Numerical Simulation
5.1. Joint Positions
Firstly, the expected trajectories of PGH,PEB, and PW were obtained using a motion capture system (Mars2H, Nokov, Nosálov, Czech Republic, sampling rate: 60 Hz). These expected trajectories were then used to determine the IK solutions θi using the method described in Section 4.1. The determined IK solutions θ iwere finally substituted into FK to calculate the joint positions to compare with the expected ones. The resolution of the exoskeleton joints was considered to improve the realism of the simulation.

Citation Wang J, Pei S, Guo J, et al. A Vector-Based Motion Retargeting Approach for Exoskeletons with Shoulder Girdle Mechanism[J]. Biomimetics, 2025, 10(5): 312.

Link https://webofscience.clarivate.cn/wos/alldb/full-record/WOS:001496699800001

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Adaptive control of lower limb robot based on human comfort under minimum inertial parameters

Keywords

Gait data analysis; Comfortable function; Minimum inertia parameters; Adapt tracking control

Abstract

For patients with dyskinesia caused by central nervous system diseases such as stroke, the lower limb rehabilitation robot is required to provide passive rehabilitation training during the initial rehabilitation training, and a trajectory for healthy human body is used as a reference trajectory, this paper designs an adaptive controller to help patients with rehabilitation training methods. First, the gait trajectory of a healthy human body is obtained using an optical motion capture system and used as a reference trajectory for rehabilitation training. Then, the unilateral oscillating leg of the lower limb rehabilitation robot is modeled by dynamics. Based on this, an adaptive controller is designed to enable the lower limb rehabilitation robot to quickly track the desired trajectory, and a similarity function for evaluating the follow ability of the lower limb rehabilitation robot is proposed. Finally, experiments on the prototype of MATLAB simulation and lower limb rehabilitation robot demonstrates the feasibility of the proposed method.

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How NOKOV Contributes to the Research

In most human gait acquisition devices, optical motion capture is preferred because it can accurately measure small reflective markers attached to some relevant body landmarks. Therefore, in this paper, theNOKOV3d infrared passive optical motion capture system is used to collect human movement gait data as input data of exoskeleton robot controller, and then proposes a human body comfort function based on human-computer interaction, in the case of model parameter uncertainty adaptive controller is designed for lower limb rehabilitation robot trajectory tracking control, so as to realize more comfortable natural gait trajectory, and improve the efficiency of rehabilitation, finally simulation experiment and in lower limb exoskeleton rehabilitation training robot experiments verify the feasibility and effectiveness of the proposed method.

Citation Hu N, Wang A, Yu J, et al. Adaptive control of lower limb robot based on human comfort under minimum inertial parameters[C]//2019 International Conference on Advanced Mechatronic Systems (ICAMechS). IEEE, 2019: 40-45.

Link https://ieeexplore.ieee.org/abstract/document/8861655

An adaptive stair-ascending gait generation approach based on depth camera for lower limb exoskeleton

Abstract

The mobility on stairways is a daily challenge for seniors and people with dyskinesia. Lower limb exoskeletons can be effective assistants to improve their life quality. In this paper, we present an adaptive stair-ascending gait generation algorithm based on a depth camera for lower limb exoskeletons. We first construct a linked-list-based stairway model with the point cloud captured from the depth camera. Then, an optimal foothold point is calculated based on the linked-list stair model for gait generation. Finally, the exoskeleton takes the stair-ascending gait of healthy people as a reference and generates appropriate gait for the stair. The proposed gait generation algorithm is initially validated through holistic simulation analyses. We tested the stairway modeling algorithm on varieties of indoor and outdoor stairways and evaluated the gait generation algorithm on stairs of different height. The subjects' stair walking tests with lower limb exoskeletons show the effectiveness of the proposed stairway modeling and gait generation approaches.

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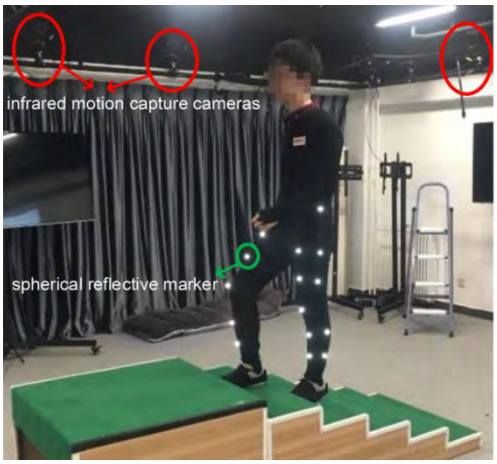

How NOKOV Contributes to the Research

To generate a natural stair walking gait as a reference, we built a motion capture site and collected a series of motion postures of healthy people walking on flat ground and stairs with the NOKOV motion capture system (Fig. 3). The infrared cameras capture the 3D location of each spherical reflective markers on the suit, and the motion posture analysis software associates each marker to a specific position of a human model. During the marker association process, all the incorrect markers with the wrong position are identified and removed manually. Then, the lower limbs and torso are fitted with the position of the markers. In this research, we denote the sequence of hip joint angles (α) and knee joint angles (β) as the lower limb exoskeleton walking gait. Hence, we can compute and filter the joint angles (α and β) with the fitted limbs and torso. Each gait angle data are fitted by an 8th order multiple sinusoidal functions for a smooth reference average gait curve,

Citation Zhao X, Chen W H, Li B, et al. An adaptive stair-ascending gait generation approach based on depth camera for lower limb exoskeleton[J]. Review of Scientific Instruments, 2019, 90(12).

Link https://pubs.aip.org/aip/rsi/article-abstract/90/12/125112/1060182/An-adaptive-stair-ascending-gait-generation?redirectedFrom=fulltext

Analysis of the Sit-to-Stand Movement Based on Dynamic Stability

Keywords

dynamic stability, COM, XCOM, SIT-to-Stand

Abstract

Sit-to-Stand (STS) is one of the most frequent movements in people's daily life. For patients with muscle weakness or paraplegia, exoskeleton assistance is an effective way to resume their ability to STS. And STS is a dynamic process of movement, so the torque of exoskeleton is gradually constructed. Therefore, analysis of the STS process is an important foundation for exoskeleton assist human to stand. In previous studies, most used methods based on mode recognition to determine the phase of the STS. However, pattern recognition methods are poorly interpretable and are affected by training samples and human motion variability. In this paper, based on the dynamic stability analysis of STS movement, we proposed a phase estimation algorithm that considers velocity variation. Six healthy volunteers were recruited in the experiment. The effectiveness of the method mentioned was verified by comparing the changes of XCOM and COM. This model-based method has better interpretability and provides a new means to analyze STS movement.

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How NOKOV Contributes to the Research

The experiment captured the 3D coordinates of the Markset through the NOKOV optical 3D motion capture system. The position of the MarkSet on the body is referenced to the Markset on the OpenSim software open-source model 3D Gait Model 2392.
First of all, OpenSim analyzes the data collected by Nokov to obtain data such as joint angles and COM in the STS movement.

Citation Fang G, Gong P, Xiang K, et al. Analysis of the Sit-to-Stand Movement Based on Dynamic Stability[C]//2023 9th International Conference on Electrical Engineering, Control and Robotics (EECR). IEEE, 2023: 1-4.

Link https://ieeexplore.ieee.org/abstract/document/10150046

Attention-Inspired Path Prediction and Adaptive Obstacle Perception Architecture for Powered Lower-Limb Prostheses

Keywords

Inertial measurement unit (IMU), lower-limb prosthesis, obstacle perception, path prediction, RGB-D camera

Abstract

Path prediction and obstacle perception are crucial intelligence capabilities for powered lower-limb prostheses (PLLPs). These capabilities enable the devices to understand the amputee's movement intentions and the walking environment, thereby enhancing the navigation abilities of PLLPs. However, it is challenging for PLLPs to achieve ideal navigation performance by relying solely on force/motion sensors. The human vision system can quickly perceive and focus on obstacles during locomotion and conduct obstacle analysis, demonstrating the potential application of vision sensors in PLLPs' navigation. This article reports an attention-inspired path prediction and adaptive obstacle perception architecture (AI-PPOPA). The architecture consists of four modules: visual odometry, object detection, path prediction, and obstacle information estimation, which enables PLLPs to realize path prediction, obstacle perception and information estimation, and real-time obstacle localization. We deployed the system on the Nvidia Jetson AGX Orin for experimental testing. The experimental results indicate that the RMSE for the distance estimation accuracy for small obstacles ranges from as high as 2.81 ± 1.06 cm to as low as 4.98 ± 1.58 cm, while for medium obstacles, it ranges from as high as 4.62 ± 1.11 cm to as low as 5.46 ± 3.45 cm. Additionally, processing images at 84 ms per image demonstrates its capability for real-time control and improves the adaptability of PLLPs in complex terrain, allowing the amputee to walk more safely.

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Fig. 7. Principal schematic for (a) experimental setup, (b) scenario, and (c) obstacle layout.

How NOKOV Contributes to the Research

Moreover, to facilitate the human wearing of the camera, the camera mounting bracket was ingeniously designed based on the structure of eyeglass frames to ensure the stability and comfort of wearing. A motion capture system (NOKOV, Beijing, China) consisting of 32 cameras sampled at 100 Hz was used to record the motion trajectory of the target points on the camera, thereby obtaining the motion trajectory of the camera in the motion capture system's coordinate system. Based on the camera's structure and coordinate system definition, four target points were placed to capture both the motion trajectory of the camera's center point and its real-time orientation.

Citation Song C, Chen C, Lv Y, et al. Attention-inspired path prediction and adaptive obstacle perception architecture for powered lower-limb prostheses[J]. IEEE Sensors Journal, 2025.

Link https://ieeexplore.ieee.org/document/10971905

Cost Function Determination for Human Lifting Motion via the Bilevel Optimization Technology

Keywords

inverse optimization control; bilevel optimization; direct collocation; particle swarm optimization; human lifting motion;

Abstract

Investigating the optimal control strategy involved in human lifting motion can provide meritorious insights on designing and controlling wearable robotic devices to release human low-back pain and fatigue. However, determining the latent cost function regarding this motion remains challenging due to the complexities of the human central nervous system. Recently, it has been discovered that the underlying cost function of a biological motion can be identified from an inverse optimization control (IOC) issue, which can be handled via the bilevel optimization technology. Inspired by this discovery, this work is dedicated to studying the underlying cost function of human lifting tasks through the bilevel optimization technology. To this end, a nested bilevel optimization approach is developed by integrating particle swarm optimization (PSO) with the direction collocation (DC) method. The upper level optimizer leverages particle swarm optimization to optimize weighting parameters among different predefined performance criteria in the cost function while minimizing the kinematic error between the experimental data and the result predicted by the lower level optimizer. The lower level optimizer implements the direction collocation method to predict human kinematic and dynamic information based on the human musculoskeletal model inserted into OpenSim. Following after a benchmark study, the developed method is evaluated by experimental tests on different subjects. The experimental results reveal that the proposed method is effective at finding the cost function of human lifting tasks. Thus, the proposed method could be regarded as a paramount alternative in the predictive simulation of human lifting motion.

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How NOKOV Contributes to the Research

o verify the developed method on the IOC issue of human lifting motion, six healthy male subjects (age: 23 ± 2 years, mass: 62.5 ±4.52 kg, height: 1.71 ± 0.101 m) have been recruited to carry out a pack with 10 kg in our experimental study. The experimental kinematic data of each subject is obtained by using a motion capture system (Nokov, Beijing Metrology Technology Co., Ltd.) with 39 marker points. For more details about ways of sticking markers, the reader can refer to the operation guidance from OpenSim official website (https://simtk-confluence.stanford.edu:8443/display/OpenSim/Gait+2392+and+2354+Models). After gaining experimental kinematic data, the musculoskeletal model is scaled by the scaling tool in OpenSim to change the anthropometry of the model in order to match the specific subject as far as possible. Note that joint kinematics and kinetics data (e.g. , joint angles and torques) are gained by inverse kinematics and inverse dynamics tools in OpenSim.

Citation Tang B, Peng Y, Luo J, et al. Cost function determination for human lifting motion via the Bilevel optimization technology[J]. Frontiers in Bioengineering and Biotechnology, 2022, 10: 883633.

Link https://www.frontiersin.org/journals/bioengineering-and-biotechnology/articles/10.3389/fbioe.2022.883633/full

Demonstration Learning and Generalization of Robotic Motor Skills Based on Wearable Motion Tracking Sensors

Keywords

Robots, Trajectory, Task analysis, Motion capture, Robot sensing systems, Optimization, Heuristic algorithms

Abstract

Learning from demonstration (LfD) is an important way for robots to learn new skills. Its principle is to obtain an optimized trajectory through an instructor's action teaching or action coding regression. By learning the teaching trajectory, the robot can master the movement skills. However, adapting the learned motor skills to meet additional constraints that arise during the task can be challenging. This article proposed a noise exploration method policy improvement through black-box optimization with an adaptive covariance matrix (PI BB -CMA), which improves the PI BB algorithm by using an adaptive covariance matrix. In our method, the teaching trajectory is collected with our designed inertial motion capture system. After that, a more reasonable trajectory is synthesized as the input to dynamic movement primitives (DMPs) using the Gaussian mixture model (GMM) and Gaussian mixture regression (GMR). Finally, the improved algorithm PI BB -CMA is used to perform noise exploration to ensure that the robot arm can pass the designated points in the path planning. Furthermore, three baseline methods are chosen for comparison to validate the robustness of our proposed method. The experimental results demonstrated that our proposed method outperforms the baseline algorithms and is feasible for improving robot intelligence. We believe that our method has a certain potential in the aspect of skill learning for robots.

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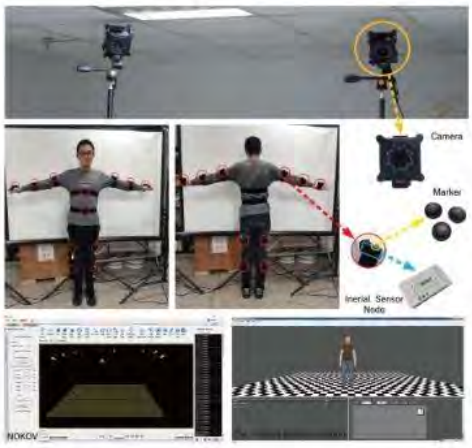

Fig. 4. Overview of the validation experiment for NOKOV and our system.

TABLE II
ESTIMATION CURVES COMPARISON BETWEEN OUR METHOD AND NOKOV

Coordinates axis	Correlation coefficient
x	0.9876
y	0.9912
z	0.9991

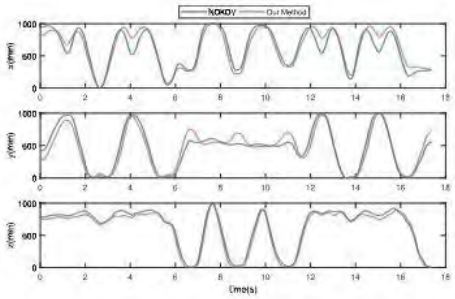

Fig. 5. Comparison of attitude data collected by NOKOV and our method.

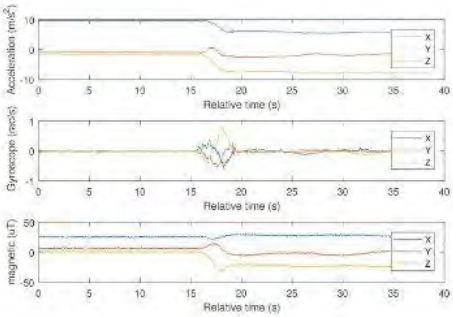

Fig. 6. Sensor data collected while writing the letter e.

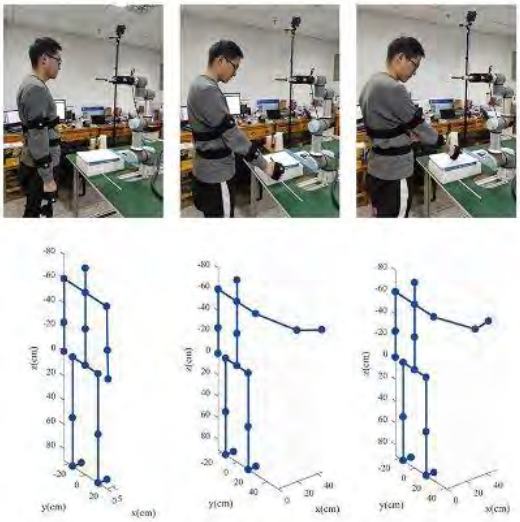

Fig. 7. Human posture corresponding to the upright, raised hand, and writing during the demonstration.

How NOKOV Contributes to the Research

In the experiment, the golden standard, optical system NOKOV, was chosen for validating the accuracy of trajectory tracking. Imitative learning and obstacle avoidance experiments are also carried out to assess the feasibility of the proposed algorithm.

Citation Liu X, Wang Z, Li J, et al. Demonstration learning and generalization of robotic motor skills based on wearable motion tracking sensors[J]. IEEE Transactions on Instrumentation and Measurement, 2023, 72: 1-15.

Link https://ieeexplore.ieee.org/abstract/document/10159577

Design and Validation of an Inertial Motion Capture System for Human Dynamic Balance Assessment

Keywords

Legged locomotion, Training, Motion segmentation, Dynamics, Motion capture, Stability analysis, Reliability, Root mean square, Monitoring, Sports

Abstract

The assessment of human balance ability holds significant clinical importance for enhancing health, preventing injuries, monitoring rehabilitation progress, and optimizing sports and physical training programs. This study introduced a system with 17 low-cost inertial measurement units (IMUs) to capture human motion data and analyze balance parameters, providing essential balance analysis for clinical patients. Initially, we utilized the inertial motion capture system to collect full-body motion IMU data and fed the data into OpenSim's human body model for calculating and analyzing gait kinematics. Subsequently, we calculated kinematic parameters relevant to human balance assessment based on human motion characteristics. To validate the feasibility of our approach, we recruited two subjects for walking experiments. We computed parameters related to human gait, posture control, and joint range of motion from the IMU data collected. These parameters were compared with those from an optical motion capture system, which was considered as the gold standard. The inertial motion capture system exhibited a root mean square error (RMSE) of 0.027 m for stride length, 0.031 m for lateral swing position of the lower limb segment center of mass, 0.010 m for vertical swing position of the lower limb segment center of mass, 7.2° for knee joint flexion angles, and 5.1° for elbow joint flexion angles. The results indicate that the newly developed inertial motion capture system and method accurately estimated parameters related to dynamic balance, showing potential for practical applications and can be used as a reliable tool for gait analysis and balance assessment in various settings.

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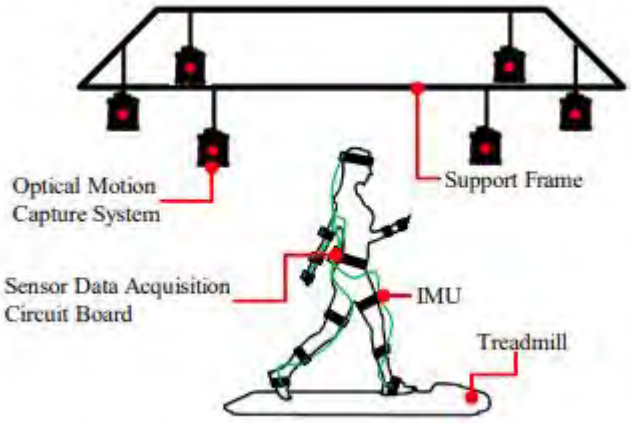

Figure 4. Inertial motion capture system and optical capture system

How NOKOV Contributes to the Research

The experimental setup, as shown in Fig. 4, incorporates both an inertial motion capture system and an optical motion capture system.
1\) The self-developed human motion capture system included a computer, an inertial motion capture system, with a sampling frequency of 100Hz.
2\) The optical motion capture system consisted of 12 NOKOV motion capture cameras (NOKOV motion capture system, Beijing, China), with a sampling frequency of 100Hz.

Citation Zhang L, Fan B, Zhang K, et al. Design and Validation of an Inertial Motion Capture System for Human Dynamic Balance Assessment[C]//2024 World Rehabilitation Robot Convention (WRRC). IEEE, 2024: 1-4.

Link https://ieeexplore.ieee.org/document/10696602

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Design of a Dynamic Waist Strap for Reducing Migration of Knee Exoskeletons

Keywords

Dynamic waist strap · Downward sliding · Thigh cuff · Knee exoskeleton

Abstract

As a key element of knee exoskeleton, the stability of thigh cuff is essential to ensure the force acting on the motion of knee without failure. The challenge of its design is preventing the cuff downward sliding when external downward force exists. Generally, it is in virtue of the friction force between the cuff and skin, so the cuff being tighter means more reliable. However, for the thigh with the large cross area in the proximal part and the small cross area in the distal part, only depend on the tightness is not feasible, meanwhile it will limit the muscle activation and cause discomfort and pain. To address this problem, we propose a dynamic waist strap (DWS) where thigh cuff is connected to a waist belt though ropes dynamically. To verify the effectiveness of proposed DWS, a serious of contrast experiments based on a textile waist belt for rock climbing and a custom thigh cuff made of thermoplastic polyurethanes (TPU) are implemented. The results indicate this design can prevent the knee exoskeleton from downward sliding more effectively compared with three existing knee exoskeleton wearing forms. The thigh cuff supported by proposed DWS only slides down by 0.505 mm after the whole experimental process is finished, far less than the data in other conditions (10.525 mm, 19.234 mm and 30.538 mm respectively), when the interaction force between thigh cuff and waist belt is not large. This research highlights the importance of waist belt when attaching a knee exoskeleton to human and introduces a new dynamic interaction interface to improve the coupling from an exoskeleton to an individual.

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Fig. 1. The prototype of proposed dynamic waist strap (DWS). The red arrows in (a) represent the external forces applied to thigh cuff and waist belt. The black arrows in (d) and (e) represent the movement direction of rope and anchor.

How NOKOV Contributes to the Research

3 Experimental Setup and Protocol
The developed method is verified by comparing the simulation results obtained by our designed simulation platform with the experimental results. Prior to conducting experimental tests, a healthy volunteer without neuro musculoskeletal problems participate in two motor tasks in this study. The kinematics of the recruited volunteer are recorded in a Nokov optical three-dimensional motion capture system (Beijing NOKOV Science \&Technology, 50 Hz) with eight high-definition cameras. Six reflective markers are placed on the medial and lateral shank and toes of the right leg to calculate the angle of the ankle.The muscle EMG signals of SOL and TA are measured by electromyography (ELONXIEMG 100-Ch-Y-RA). In the preparation of the experiment, the leg hairs of the subjects are removed and the skin is cleaned with alcohol. After that, EMG activity levels during maximal isometric voluntary contractions (MVC) are measured in standard muscletesting position for the subject before the experiment and used to normalize the EMG signals. The sampling frequencies of Nokov and EMG are 50 Hz and 1000 Hz, respectively Moreover, we implement the real-time simulator to achieve the synchronous reception of experimental data.

Citation Xu M, Zhou Z, Shao J, et al. Design of a dynamic waist strap for reducing migration of knee exoskeletons[C]//International Conference on Intelligent Robotics and Applications. Cham: Springer International Publishing, 2021: 687-697.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:000725380900065

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Designing Kresling Origami for Personalised Wrist Orthosis

Keywords

Wrist, Training, Heating systems, Hands, Shape, Bending, Soft robotics, Motors, Fabrics, Tendons

Abstract

The wrist plays a pivotal role in facilitating motion dexterity and hand functions. Wrist orthoses, from passive braces to active exoskeletons, provide an effective solution for the assistance and rehabilitation of motor abilities. However, the type of motions facilitated by currently available orthoses is limited, with little emphasis on personalised design. To address these gaps, this paper proposes a novel wrist orthosis design inspired by the Kresling origami. The design can be adapted to accommodate various individual shape parameters, which benefits from the topological variations and intrinsic compliance of origami. Heat-sealable fabrics are used to replicate the non-rigid nature of the Kresling origami. The orthosis is capable of six distinct motion modes with a detachable tendon-based actuation system. Experimental characterisation of the workspace has been conducted by activating tendons individually. The maximum bending angle in each direction ranges from 18.81° to 32.63°. When tendons are pulled in combination, the maximum bending angles in the dorsal, palmar, radial, and ulnar directions are 31.66°, 30.38°, 27.14°, and 14.92°, respectively. The capability to generate complex motions such as the dart-throwing motion and circumduction has also been experimentally validated. The work presents a promising foundation for the development of personalised wrist orthoses for training and rehabilitation.

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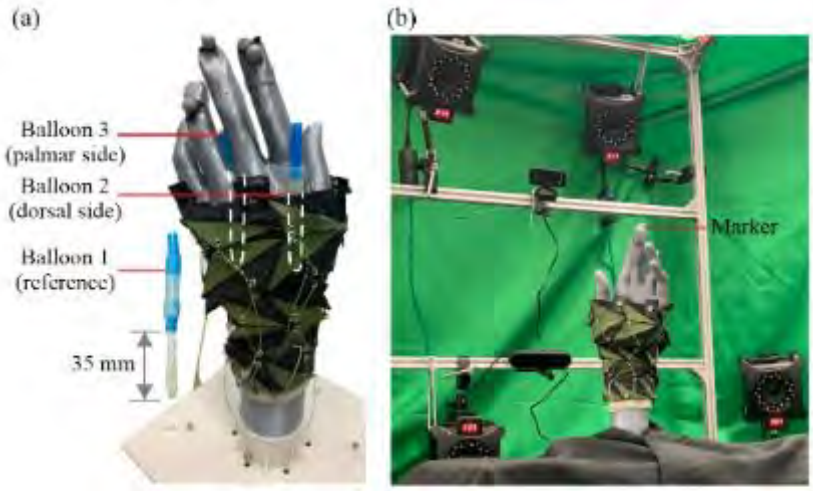

Fig. 5. Experimental setups. (a) Balloons for custom fit evaluation. (b) Actuated wrist orthosis in the motion tracking system for workspace and movement characterisation.

How NOKOV Contributes to the Research

Model 2 with Orthosis 2 was placed under a motion tracking system, MARS4H (NOKOV Ltd, China) to characterise its workspace and specific movements as shown in5(b). Three markers were attached to the index, middle, and ring fingers, whose positions were recorded. The following motions were conducted and repeated 3 times each.

Citation Liu C, Mao S, Lei Y, et al. Designing Kresling Origami for Personalised Wrist Orthosis[C]//2025 IEEE 8th International Conference on Soft Robotics (RoboSoft). IEEE, 2025: 1-7.

Link https://ieeexplore.ieee.org/document/11020928

Dual-Loop Control Framework of a Self-Balancing Lower-Limb Exoskeleton for Assisted Walking

Keywords

Centroid dynamics, deformation estimator, dual-loop control, exoskeleton, linear quadratic regulator.

Abstract

This article describes a dual-loop control frame work of self-balancing lower-limb exoskeletons (SBLLEs) to estimate deformations and to stabilize SBLLEs for assisted walking tasks conducted on wearers with diverse physical param eters. First, considering the nonlinear time-varying characteristic of deformation and the time dependency and periodic nature of walking motion, a bidirectional long short-term memory (Bi-LSTM) neural network is utilized to estimate multiple defor mations. In particular, the force sensor and Bi-LSTM-based deformation estimator (FBDE) loop are used to estimate and compensate for the deformation based on the force and moment signals. Second, a physical parameter-independent controller (PPIC) based on centroidal dynamics is proposed to stabilize exoskeletons that can accommodate wearers with varying physi cal parameters. The PPIC loop is also based on force and moment signals, indicating that only 6-D force sensors are necessary to estimate deformation and stabilize SBLLEs. Finally, a series of experiments is conducted on three subjects with varying physical parameters to validate the effectiveness of the dual-loop control framework. The results of walking experiments show that the dual-loop control framework can estimate deformation and stabilize the SBLLE during walking under different loads.

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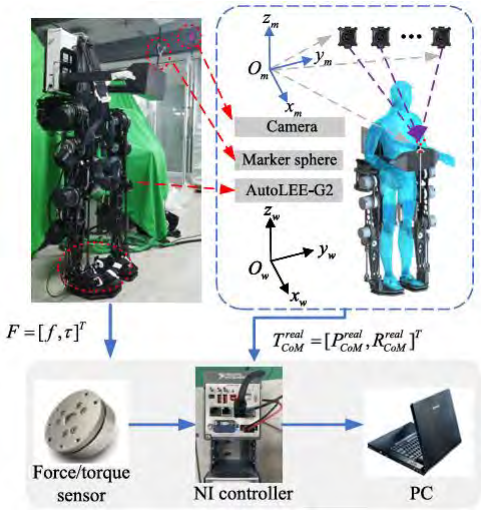

Fig. 6. Data acquisition platform for AutoLEE-G2.

How NOKOV Contributes to the Research

Fig. 6 shows the experimental platform. The SBLLE AutoLEE-G2 was placed in the NOKOV high precision motion capture environment ∑Om.

Citation D. Tian et al., "Dual-Loop Control Framework of a Self-Balancing Lower-Limb Exoskeleton for Assisted Walking," in IEEE Transactions on Instrumentation and Measurement, vol. 73, pp. 1-11, 2024, Art no. 7506511, doi: 10.1109/TIM.2024.3440384.

Link https://ieeexplore.ieee.org/document/10637283

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Effect of wearable chair on gait, balance, and discomfort of new users during level walking with anterior loads

Keywords

Wearable Chair， Gait Balance， Discomfort， Ergonomics， Occupational Health

Abstract

Introduction: Walking with anterior loads is common in industrial scenarios, but as exoskeletons are increasingly used in work environments to alleviate musculoskeletal disorders (MSDs), this new "human-robot" system composed of the human body and exoskeleton may be associated with new risks and harm that warrant further investigation. Therefore, this study will discuss the effect of a wearable chair on the gait, balance, and discomfort of new users with different weights of anterior loads during level walking. Method: Twenty-two healthy subjects (sex balanced) participated in the experiment. Each exposure comprised one of two exoskeleton states (with/without) and four load conditions: No carried load, carrying an empty box (0.3 kg), 5%Body Weight (BW), and 10%BW. The order of exoskeleton states and load conditions was randomly assigned. Using an eight-camera motion capture system to record the entire movement. And the subjective discomfort and perceived balance after each exposure were recorded on an 11-point numeric rating scale, respectively. Using SPSS 26.0 software (IBM Inc., Chicago) to conduct statistical analyses. Results: Level walking with a wearable chair in different load conditions significantly affected gait parameters (like cadence) and gait balance. The perceived balance decreased with the exoskeleton, consistent with objective results. For subjective discomfort, wearing the exoskeleton significantly impacted global discomfort. Also, it increased the local discomfort of the shoulders, waist, thighs, shanks, and feet/ankles. Conclusions: For new users, the risk of losing balance or falling may be increased when wearing an exoskeleton for non-target task behaviors (level walking/anterior load), and caution is recommended when the anterior load exceeds 5% BW. Practical Application: The proposed strategy for assessing human gait, balance, and discomfort in wearable chairs may be applied during the iterative design of the product. These controls will help develop training programs and implementation guidelines for this exoskeleton type.

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Fig. 2. Helen Hayes posting points (25 in total) diagram in the study, the location of the posting points is circled in green in the figure.

How NOKOV Contributes to the Research

An eight-camera motion capture system was used to record movements (NOKOV, China). A standard gait analysis model, the Helen Hayes (HH) model, was used for tagging (Collins et al.,2009; Kadaba et al., 1990). Twenty-five small optical infrared reflective balls were tagged on the subject's head, trunk, and upperand lower extremities, and the tagged locations were sampled at64 Hz (SeeFig. 2). All data were recorded using NOKOV software and stored on a dedicated desktop computer for later processing.

Citation Li Y Y, Gan J. Effect of wearable chair on gait, balance, and discomfort of new users during level walking with anterior loads[J]. Journal of safety research, 2023, 87: 27-37.

Link https://www.sciencedirect.com/science/article/abs/pii/S0022437523001159

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Enabling 6D Pose Tracking on Your Acoustic Devices

Keywords

Acoustic signal, FMCW, pose tracking, 6DoF, band multiplexing

Abstract

The ubiquity of acoustic devices and the fine-grained sensing of acoustic signals have made acoustic device tracking a popular option. We propose to expand the use of commercial devices with microphones as an extension of the audio system to support intelligent applications, such as VR/AR. This paper introduces a novel 6D acoustic pose estimation system. To realize device-based pose estimation, most existing systems deploy multiple speakers. However, due to limited inaudible bandwidth, concurrent transmissions with multiple speakers pose challenges in balancing resolution and frame rate. To address this problem, we design 2×Track, a band multiplexing signal model that doubles the availability of limited bandwidth by utilizing a unique encoding strategy for concurrent transmissions. We also propose solutions to enhance signal feature estimation and implement a 6DoF pose tracking scheme tailored for distributed systems. The prototype is deployed on a typical circular microphone array, and experimental results show that 2×Track achieves a median position and orientation error of 7.6mm and 4.1°, respectively, in a 4-speaker setup. Our extended applications on commercial devices also showcase the versatility of our system, particularly in face orientation detection, air mouse and drone tracking.

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(a) Respeaker. (b) Motion capture system.

Figure 12: Implemention.

(a) (b) (c)

Figure 22: Apply 2×Track to drone tracking.

How NOKOV Contributes to the Research

Ground truth measurement.We use the NOKOV motion capture system \[1] to capture the 6DoF Ground Truth.

Citation Wu Y, Chen S, Meng X, et al. Enabling 6d pose tracking on your acoustic devices[C]//Proceedings of the 22nd Annual International Conference on Mobile Systems, Applications and Services. 2024: 15-28.

Link https://dl.acm.org/doi/10.1145/3643832.3661875

Enhanced Gait Prediction Using RNN-LSTM: A Synergistic Approach with Motion Capture and OpenSim

Keywords

Gait trajectory generation, Motion Capture System, OpenSim, LSTM-CNN, RNN-LSTM

Abstract

Predicting gait trajectories plays a crucial role in biomechanical studies, rehabilitation, and the development of assistive devices. This study aims to use deep learning to predict and generate personalized gait trajectories based on a person's physical characteristics, including age, height, weight, gender, and the length of their ankles and knees. A Comparison of deep learning models, including Convolutional Neural Network (CNN), Long Short-Term Memory (LSTM), Gated Recurrent Unit (GRU), and hybrid models, a sequential combination of LSTM-CNN and Recurrent Neural Network-LSTM is presented to enhance predictive accuracy by selecting the most suitable model for gait prediction, thereby contributing to personalized gait analysis and rehabilitation strategies. These models were trained by Gait data, comprising joint coordinates as a function of time from 28 subjects walking at various speeds, using the NOKOV motion capture system and processed through OpenSim. This study focused on healthy individuals with normal gait to facilitate control of a lower limb exoskeleton based on predicted gait trajectories. From the comparative analysis, the hybrid RNN-LSTM model demonstrated improved stability in gait prediction with a mean squared error (MSE) of 1.29, coefficient of determination (\\(R^2\\)) of 0.94, and Pearson correlation coefficient (PCC) of 0.97, compared to other models in terms of accuracy, efficiency, and computational time. The results also highlight the potential of deep learning approaches in predicting gait abnormalities by comparing predicted trajectories with actual gait patterns.

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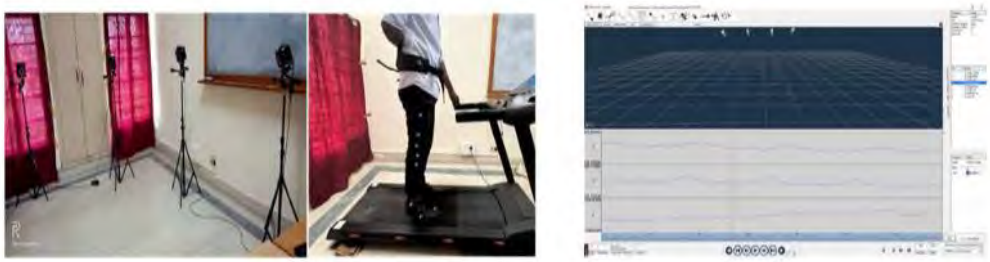

Fig. 2. (a) Experimental Setup Markers on the Subject; (b) Subject Markers 3D view along with XYZ graphs

How NOKOV Contributes to the Research

Predicting gait trajectories plays a crucial role in biomechanical studies, rehabilitation, and the development of assistive devices. This study aims to use deep learning to predict and generate personalized gait trajectories based on a person's physical characteristics, including age, height, weight, gender, and the length of their ankles and knees. A comparison of deep learning models, including Convolutional Neural Network (CNN), Long Short-Term Memory (LSTM), Gated Recurrent Unit (GRU), and hybrid models, a sequential combination of LSTM-CNN and Recurrent Neural Network-LSTM is presented to enhance predictive accuracy by selecting the most suitable model for gait prediction, thereby contributing to personalized gait analysis and rehabilitation strategies. These models were trained by gait data, comprising joint coordinates as a function of time from 28 subjects walking at various speeds using the NOKOV motion capture system and processed through OpenSim. This study focused on healthy individuals with normal gait to facilitate control of a lower limb exoskeleton based on predicted gait trajectories. From the comparative analysis, the hybrid RNN-LSTM model demonstrated improved stability in gait prediction with a mean squared error (MSE) of 1.29, coefficient of determination (R^2) of 0.94, and Pearson correlation coefficient (PCC) of 0.97, compared to other models in terms of accuracy, efficiency, and computational time. The results also highlight the potential of deep learning approaches in predicting gait abnormalities by comparing predicted trajectories with actual gait patterns.

Citation Deenadayalan E. Enhanced Gait Prediction Using RNN-LSTM: A Synergistic Approach with Motion Capture and OpenSim[C]//2025 International Conference on Power, Instrumentation, Control, and Computing (PICC). IEEE, 2025: 1-6.

Link https://ieeexplore.ieee.org/document/11291340

Estimation of the interaction force between human and passive lower limb exoskeleton device during level ground walking

Keywords

Interaction force estimation; Passive lower limb exoskeleton; Level ground walking; Bilevel optimization

Abstract

To develop sophisticated and efficient control strategies for exoskeleton devices, acquiring the information of interaction forces between the wearer and the wearable device is essential. However, obtaining the interaction force via conventional methods, such as direct measurement using force sensors, is problematic. This paper proposes a kinematic data-based estimation method to evaluate the interaction force between human lower limbs and passive exoskeleton links during level ground walking. Unlike conventional methods, the proposed method requires no force sensors and is computationally cheaper to obtain the calculation results. To obtain more accurate kinematic data, a marker refinement algorithm based on bilevel optimization framework is adopted. The interaction force is evaluated by a spring model, which is used to imitate the binding behavior between human limbs and the exoskeleton links. The deflection of the spring model is calculated based on the assumption that the phase delay between human limb and exoskeleton link can be presented by the sequence of frames of kinematic data. Experimental results of six subjects indicate that our proposed method can estimate the interaction forces during level ground walking. Moreover, a case study of bandage location optimization is conducted to demonstrate the usefulness of obtaining the interaction information.

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How NOKOV Contributes to the Research

The subjects were asked to walk on a treadmill with a speed of 1.5 m/s for 1 min in one task. Each subject was asked to perform five tasks in two days. To evaluate the effectiveness of our proposed method, the markers were attached by different persons. The kinematic data were recorded by a passive optical motion capture system (sampling frequency 50 Hz, Nokov, Beijing Metrology Technology Co., Ltd., China).

Citation Pang M, Luo Z, Tang B, et al. Estimation of the interaction force between human and passive lower limb exoskeleton device during level ground walking[J]. Biomimetic Intelligence and Robotics, 2022, 2(3): 100056.

Link https://www.sciencedirect.com/science/article/pii/S2667379722000213

Evaluation of Muscle Activation Reaction on Fore-Aft Dynamic Interference During Load-Carrying Level Walking

Keywords

Load-carrying， Muscle activations， Fore-aft dynamic disturbance， Muscle synergy

Abstract

Loading-carrying walking is a common and important task. Since carrying load is one of the main functions of wearable robotic devices, studying human responses to the dynamic disturbance of load-carrying can help to design sophisticated control algorithms for wearable robots. However, few studies focus on the effects of for-aft direction load on locomotion and the reaction of human has not been fully analyzed. This paper studies the surface Electromyography (sEMG) reaction under the fore-aft dynamic disturbance. A backpack is designed which can exert disturbance force on fore-aft direction during level walking. Comparison experiments, with and without load backpack, are performed to obtain kinematic and sEMG data from subjects. The muscle synergy is used to evaluate the dynamic responses of subjects to the disturbance. The experimental results indicate that subjects explore new patterns, expressed by different muscles synergies, to adapt to fore-aft interference through adjusting muscle activations. The obtained results may hint that human beings tend to utilize ankle strategy to exert fore-aft disturbance during level walking.

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Fig. 3. EMG electrode locations and data acquisition framework

How NOKOV Contributes to the Research

In order to divide a complete gait cycle of the experimenter, the NOKOV optical 3D motion capture system was used to capture the information of the experimenter' smotion. The overall data acquisition framework of the experimental system was indicatedin Fig.3B.

Citation Liu K, Xiang K, Tang B, et al. Evaluation of Muscle Activation Reaction on Fore-Aft Dynamic Interference During Load-Carrying Level Walking[C]//International Conference on Intelligent Robotics and Applications. Cham: Springer International Publishing, 2022: 626-636.

Link https://link.springer.com/chapter/10.1007/978-3-031-13841-6_56

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Evaluation of Muscle Activation Reaction on Vertical Climbing

Keywords

Vertical climbing, sEMG, Muscle synergy, NNMF

Abstract

Vertical climbing is a common movement in industrial field, which requires coordination of entire body joints and is a high-risk task for workers. Exoskeletons have the ability to assist wear to perform vertical climbing and reduce the risk of failed motion. However, raw studies have paid attention on exoskeleton-assisted vertical climbing. In order to develop vertical climbing assistance strategy for exoskeleton system, it is essential to obtain the inherent control strategy of human subject for this movement. Muscle activations, which can be observed by surface Electromyography (sEMG) signals, are able to present muscle activity or human potential control intent. Therefore, we adopt muscle synergy technology to analyze human vertical climbing movement. Firstly, the whole process is divided into four phases according to the movement data and sEMG data collected in experiment. Then, the preprocessed signals were decomposed using a non-negative matrix factorization (NNMF) algorithm. Finally, four muscle synergistic responses are extracted by variance accounted for (VAF) approach. The results of the experiments showed that the subjects' muscle synergy between the different phases was not highly correlated. The final finding may indicate that during vertical climbing, human beings change muscle activation patterns to adapt to the impacts from body stability and to realize vertical climbing.

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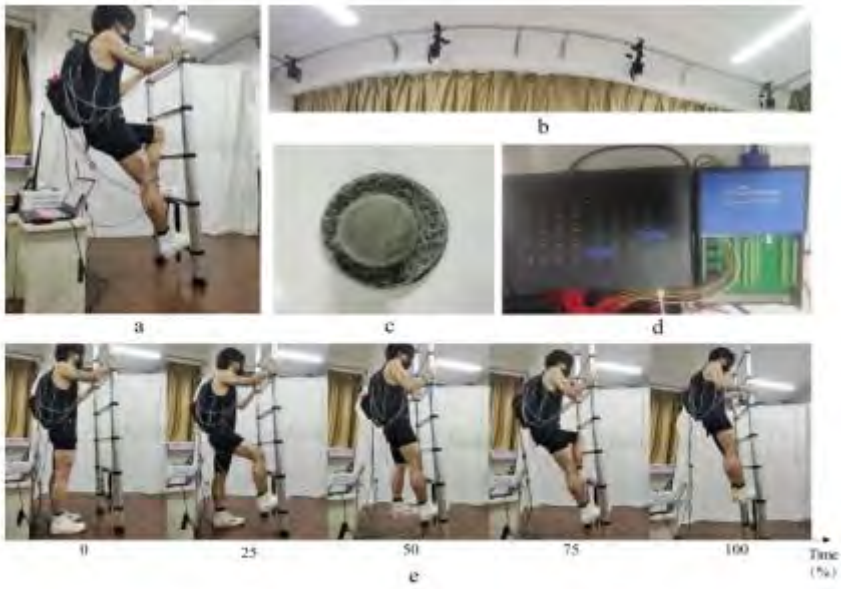

Fig. 1. The experiment collection equipment and entire movement process of climbing.

How NOKOV Contributes to the Research

The passive optical 3D motion capture systems (NOKOV, Beijing Metrology Technology Co., Ltd., China), as shown in Fig.1b, was used to collect kinematic data with a sampling frequency of 50 Hz. Based on the Helen Hayes model and combined with the needs of this experiment, we finally chose to place 41 markers on the whole body of the subject.

Citation Wang L, Pang M, Xiang K, et al. Evaluation of Muscle Activation Reaction on Vertical Climbing[C]//2023 9th International Conference on Electrical Engineering, Control and Robotics (EECR). IEEE, 2023: 42-45.

Link https://ieeexplore.ieee.org/document/10150130

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FSGlove: An Inertial-Based Hand Tracking System with Shape-Aware Calibration

Abstract

Accurate hand motion capture (MoCap) is vital for applications in robotics, virtual reality, and biomechanics, yet existing systems face limitations in capturing high-degree-of-freedom (DoF) joint kinematics and personalized hand shape. Commercial gloves offer up to 21 DoFs, which are insufficient for complex manipulations while neglecting shape variations that are critical for contact-rich tasks. We present FSGlove, an inertial-based system that simultaneously tracks up to 48 DoFs and reconstructs personalized hand shapes via DiffHCal, a novel calibration method. Each finger joint and the dorsum are equipped with IMUs, enabling high-resolution motion sensing. DiffHCal integrates with the parametric MANO model through differentiable optimization, resolving joint kinematics, shape parameters, and sensor misalignment during a single streamlined calibration. The system achieves state-of-the-art accuracy, with joint angle errors of less than \\(2.7^\circ\\), and outperforms commercial alternatives in shape reconstruction and contact fidelity. FSGlove's open-source hardware and software design ensures compatibility with current VR and robotics ecosystems, while its ability to capture subtle motions (e.g., fingertip rubbing) bridges the gap between human dexterity and robotic imitation. Evaluated against Nokov optical MoCap, FSGlove advances hand tracking by unifying the kinematic and contact fidelity.

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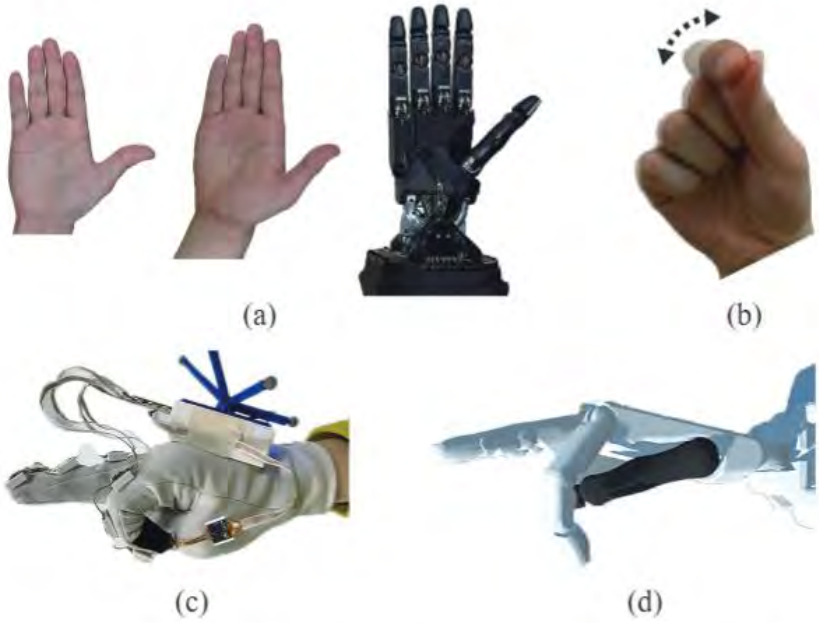

Fig. 1: **Hand shape variation.** (a) The variation in hand shapes across different human subjects and a robotic hand. (b) Thumb-index fingertip rubbing requires a slight twist DoF. (c), (d) Motion transfer often fails when adapted between hands with heterogeneous shapes, even when all the joints are mapped.

How NOKOV Contributes to the Research

While IMUs capture hand joint orientations, global translational motion requires complementary tracking. We adopt the Nokov optical system to resolve 6DoF dorsal poses.As shown in Fig. 4, a 3D-printed, tree-like structure with infrared (IR) reflective markers is mounted on the glove for stable tracking. The FPC is shielded with tape to reduce IR reflection noise.

Citation Y. Li, J. Zhang, W. Xu, T. Tang and C. Lu, "FSGlove: An Inertial-Based Hand Tracking System with Shape-Aware Calibration," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 18304-18311, doi: 10.1109/IROS60139.2025.11245803.

Link https://ieeexplore.ieee.org/document/11245803

Hierarchical MARG Fusion Method With Human Constraints for Upper Limb Motion Estimation

Keywords

Extended Kalman filter (EKF), human constraints, inertial measurement unit (IMU), magnetic, angular rate, and gravity (MARG), motion capture (MoCap)

Abstract

Motion capture (MoCap) provides technical support for human motion tracking and orientation estimation, which has enormously benefited the research of human–computer interaction in the aerospace field. Compared with the optical MoCap system, inertial measurement units (IMUs) play an irreplaceable role in accurately calculating the orientation and position of the human body without being affected by light. This article presents a novel approach that incorporates the coupling of position and orientation into the state equation, enabling accurate estimation of human motion. Also, we incorporate constraints into the optimization process using a least squares-based projection method to reduce drift and improve long-term stability. First, on the basis of the established upper limb kinematics model, the quaternion-based IMU fusion extended Kalman filter (EKF) method is leveraged to compensate roll and pitch angles. Then, the magnetic, angular rate, and gravity (MARG)-EKF method performs a complete compensation of 3-D orientation and position through the data fusion of MARG. In order to further reduce the drift, human constraints are introduced. The novel constrained MARG-EKF algorithm has been tested by various movements, which shows the position tracking accuracy in X -, Y -, and Z -axes of 10 cm. Also, the imposed constraints can reduce the error by 2.4%–15.0% for the forearm and 3.2%–11.4% for the upper arm. The experimental results represent that our proposed method can track upper limb motion more accurately with higher feasibility and stability.

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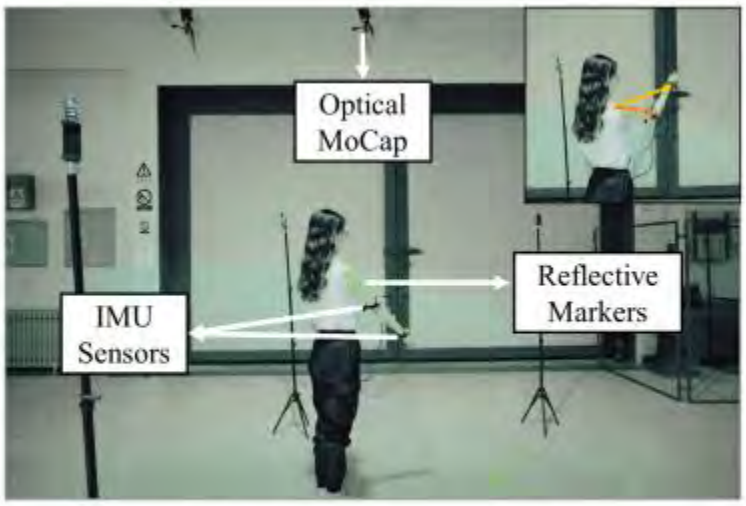

Fig. 4. Optical MoCap and MARG system setup.

How NOKOV Contributes to the Research

Except for the inertial and magnetometer sensors, 16 cameras of the Nokov optical MoCap system are evenly arranged in the laboratory, which is leveraged as a reference system for the proposed algorithm verification and RMSE comparison. The robot operating system (ROS) is utilized to achieve clock synchronization of MARG and optical MoCap system.

Citation Shi Y, Zhang Y, Li Z. Hierarchical MARG Fusion Method With Human Constraints for Upper Limb Motion Estimation[J]. IEEE Sensors Journal, 2023, 23(17): 19092-19104.

Link https://ieeexplore.ieee.org/abstract/document/10194543

Human-Gait-Based Tracking Control for Lower Limb Exoskeleton Robot

Keywords

lower limb exoskeleton robot; human gait data; radial basis function network; feed-forward control; motion capture

Abstract

Research shows that it is practical for the normal human movement mechanism to assist the patients with stroke in robot-assisted gait rehabilitation. In passive training, the effect of rehabilitation training for patients can be improved by imitating normal human walking. To make the lower limb exoskeleton robot (LLER) move like a normal human, a tracking control scheme based on human gait data is proposed in this paper. The real human gait data is obtained from healthy subjects using a three-dimensional motion capture platform (3DMCP). Furthermore, the normal human motion characteristics are adopted to enhance the scientificity and effectiveness of assistant rehabilitation training using LLER. An adaptive radial basis function network (ARBFN) controller based on feed-forward control is presented to improve the trajectory tracking accuracy and tracking performance of the control system, where the ARBFN controller is deployed to predict the uncertain model parameters. The feed-forward controller based on the tracking errors is used to compensate for the input torque of LLER. The effectiveness of the presented control scheme is confirmed by simulation results based on experimental data.

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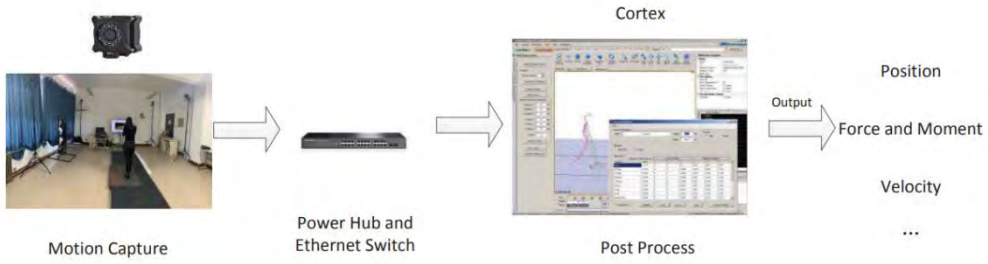

Fig. 1. Motion capture platform.

How NOKOV Contributes to the Research

Currently, a Nokov 3DMCP is utilized to obtain RHGD from healthy subjects. The 3DMCP comprises six high-performance infrared lenses (HPIL), motion capture software (Cortex), reflective markers, two calibration rods, data transmission equipment, etc. The motion capture platform is shown in Fig. 1. The HPIL is adopted to capture the spatial position of passive reflective markers, and these data are uploaded to the Cortex using data transmission equipment. The accuracy of RHGD processed by Cortex is up to sub-millimeter level, which benefits from the HPIL with the highest frequency of 240 Hz and 1.3 megapixels.

Citation Dan Y, Ge Y, Wang A, et al. Human-gait-based tracking control for lower limb exoskeleton robot[J]. Journal of Robotics and Mechatronics, 2022, 34(3): 615-621.

Link https://www.jstage.jst.go.jp/article/jrobomech/34/3/34_615/_article/-char/ja/

Human-Like Robust Adaptive PD Based Human Gait Tracking for Exoskeleton Robot

Abstract

For patients with dyskinesias caused by central nervous system diseases such as stroke, in the early stage of rehabilitation training, lower limb rehabilitation robots are used to provide passive rehabilitation training. This paper proposed a human-like robust adaptive PD control strategy of the exoskeleton robot based on healthy human gait data. When the error disturbance is bounded, a human-like robust adaptive PD control strategy is designed, which not only enables the rehabilitation exoskeleton robot to quickly track the human gait trajectory obtained through the 3D NOKOV motion capture system, but also can well identify the structural parameters of the system and avoid excessively initial output torque for the robot. MATLAB simulation verifies that the proposed method has a better performance to realize tracking the experimental trajectory of human movement and anti-interference ability under the condition of ensuring global stability for a lower limb rehabilitation exoskeleton robot.

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How NOKOV Contributes to the Research

For patients with dyskinesias caused by central nervous system diseases such as stroke, in the early stage of rehabilitation training, lower limb rehabilitation robots are used to provide passive rehabilitation training. This paper proposed a human-like robust adaptive PD control strategy of the exoskeleton robot based on healthy human gait data. When the error disturbance is bounded, a human-like robust adaptive PD control strategy is designed, which not only enables the rehabilitation exoskeleton robot to quickly track the human gait trajectory obtained through the 3D NOKOV motion capture system, but also can well identify the structural parameters of the system and avoid excessively initial output torque for the robot. MATLAB simulation verifies that the proposed method has a better performance to realize tracking the experimental trajectory of human movement and anti-interference ability under the condition of ensuring global stability for a lower limb rehabilitation exoskeleton robot.

Citation Wang A, Hu N, Yu J, et al. Human-Like Robust Adaptive PD Based Human Gait Tracking for Exoskeleton Robot[J]. Journal of Robotics and Mechatronics, 2021, 33(1): 88-96.

Link https://www.jstage.jst.go.jp/article/jrobomech/33/1/33_88/_article/-char/ja/

Indoor Relative Positioning Method and Experiment Based on Inertial Measurement Information/Human motion model/UWB Combined System

Keywords

Indoor positioning; Inertial measurement information; Human motion model; UWB

Abstract

Navigation and positioning services are related to national security, economic development and social livelihood, they're playing a decisive and indispensable role in both military and civilian fields. Urbanization is accelerating and indoor sites are increasing. People spend more than 80% of their time living and working in the indoor environments (including large buildings, underground sites, mines, tunnels, etc.), How to achieve high-precision navigation and positioning in such a complex navigation environment? This is not only an urgent social problem but also a technical problem. Based on the introduction of indoor navigation background, an inertial measurement information/UWB combined indoor positioning method is proposed in this paper, to solve the problem of long-term positioning in a complex indoor environment, and the experimental researches have been performed. Firstly, based on the research of human motion model, the method extracts motion parameters related to navigation and establishes the mapping model between human motion parameters and navigation parameters in order to implement autonomous pedestrian navigation which is based on inertial measurement information/human motion model. Then, using the position information provided by UWB as the measurement, the Kalman filter based on inertial measurement information/ human motion model/UWB combined system is designed to integrate positioning information from the combined system of inertial measurement information/human motion model and UWB, so that it can provide long-term and high-precision relative navigation for indoor pedestrians. The paper develops a prototype of the inertial measurement information/human motion model/UWB combined system, which provides a physical platform for the experimental verification of the proposed method. What's more, it also optimizes and verifies the proposed method referring to experiments under the environment of NOKOV high-precision indoor 3D-motion capture system by Beijing measurement technology co., LTD. There are bright application prospects that the method can be extended in single-soldier system, urban anti-terrorism operations and pedestrian

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positioning in the field of emergency rescue.

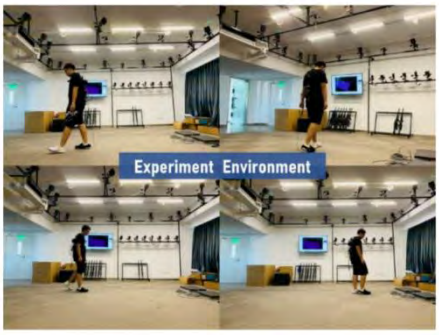

Fig. 4. Nokov 3D optical motion capture system.

How NOKOV Contributes to the Research

Nokov3D optical motion capture system is mainly composed of infrared optical motion capture lens, operation, analysis and processing software and related accessories, which can capture and output the accurate three-dimensional data of the object to be measured. The accuracy of this motion capture system can reach sub-millimeter level, which meets the requirements of evaluating the positioning accuracy of the method proposed in this paper. TheNokov3D optical motion capture system is shown as Fig. 4.

Citation Zhang Y, Wang N, Li M, et al. Indoor relative positioning method and experiment based on inertial measurement information/human motion model/UWB combined system[C]//2020 27th Saint Petersburg International Conference on Integrated Navigation Systems (ICINS). IEEE, 2020: 1-6.

Link https://ieeexplore.ieee.org/abstract/document/9134055

Kinematic Compatible Design and Analysis of a Back Exoskeleton via a Hyper RedundantHybrid Mechanism

Keywords

Back exoskeleton, hyper redundant mechanism, kinematic compatibility, mechanism design.

Abstract

Back exoskeletons can reduce low-back pain and injury for workers engaged in manual handling operations. However, conventional back exoskeletons are incompatible with human trunk kinematics, arousing uncomfortable human-exoskeleton interaction and limiting natural human movement. This article proposes a novel back exoskeleton design to solve this problem. A hyper redundant hybrid mechanism is synthesized as the exoskeleton mechanism to be compatible with the multi-DOF anatomy of the human spine. We establish the kinematic model of the coupled human-exoskeleton system and analyze the kinematic incompatibility problem. The movement of the human back is characterized by a multi-joint lumbar spine combined with a rigid thoracic spine. The proposed back exoskeleton is composed sequentially of five six-DOF passive parallel mechanisms with one cable actuation, generating active assistance in the sagittal plane and passive assistance in the coronal and transverse planes. The kinetics of the coupled human-exoskeleton system is analyzed to show effective assistance. Experimental tests on kinematic compatibility are finally implemented to demonstrate that the proposed exoskeleton allows the wearer to perform natural movements in all directions with large ranges of motion.

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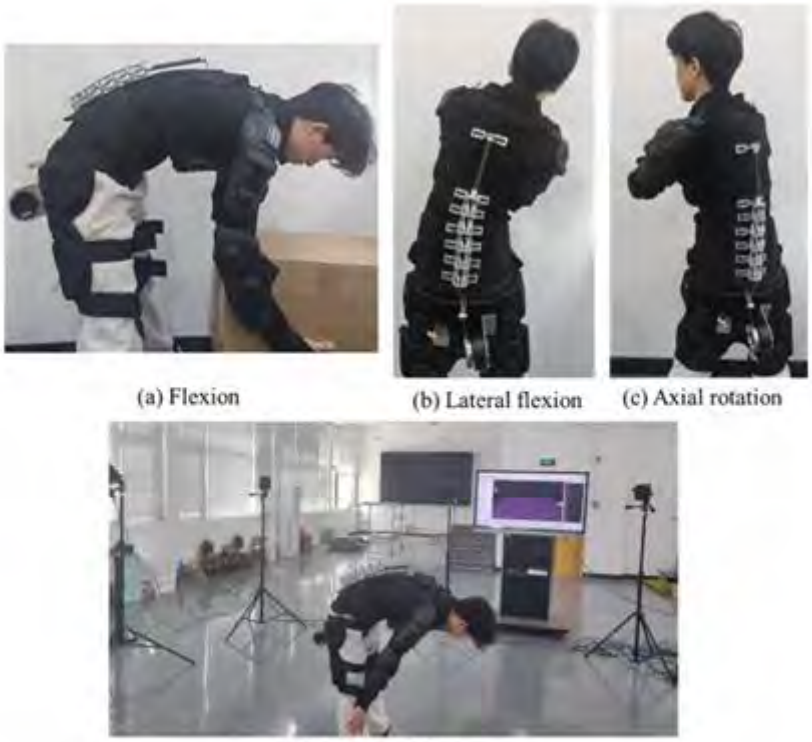

Fig. 9. The exoskeleton adapts to the shapes of the human back very well in all the three directions: (a) Flexion, (b) Lateral flexion, (c) Axial rotation. The optical motion capture system is set up to record the positions of the exoskeleton during the movement (d) Experimental Setup.

How NOKOV Contributes to the Research

We test the adaptability of the device to the different wearer postures. Three subjects participate in the tests, whose heights range from 178cm to 185cm. One can see that the exoskeleton conforms to the back shape of the wearer well in all directions (Fig. 9(a)–(c)). We then set up an optical motion capture system with eight cameras (NOKOV Mocap, CN) to record the positions of the exoskeleton on the human back during the movement (Fig. 9(d)). Accordingly, seven markers are attached to the seven disks to track the wearers' motion conveniently.

Citation Yang X, Zhou P, Sun Y, et al. Kinematic compatible design and analysis of a back exoskeleton via a hyper redundant hybrid mechanism[J]. Ieee Robotics and Automation Letters, 2022, 7(4): 11322-11329.

Link https://ieeexplore.ieee.org/document/9857997

Mechanical Compliance and Dynamic Load Isolation Design of Lower Limb Exoskeleton for Locomotion Assistance

Keywords

Compliant joint; constant-force suspension mechanism; exoskeleton; metabolic rate

Abstract

Improving the comfort and portability of exoskeleton structures for human locomotion assistance is challenging. Research shows that the misalignments between exoskeletons and human joints will lead to interference and undesired interaction forces in locomotion. Moreover, the weight and inertia of exoskeletons will lead to rapid changes in impact forces acting on the wearer. When the exoskeleton is tightly bound to the wearer's body, such forces are usually unavoidable. These issues not only reduce the comfort and portability of exoskeletons, but also increase the energy costs to wearers. To address these issues, we propose a novel lower limb exoskeleton with a constant-force suspension mechanism and self-adapting compliant joints. The constant-force suspension mechanism aims to isolate the impact force on the back of the wearer, while the self-adapting compliant joints aim to reduce the misalignments between the exoskeleton and the wearer. For the first time, a structure designed to isolate the impact force of exoskeletons is proposed. Moreover, compliant joints exhibiting comprehensive great performances in portability, flexibility, self-aligning, and weight-supporting ability have also been rarely reported. The experimental results demonstrate that the developed mechanisms can reduce the impact forces and misalignments in locomotion. Furthermore, the proposed exoskeleton can reduce the metabolic rate during walking at 5 km/h by 10.95 ± 4.40% and that during running at 9 km/h by 1.71 ± 4.54% compared with locomotion without the exoskeleton. These results confirm that the proposed designs can improve the performance of the exoskeleton in locomotion.

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How NOKOV Contributes to the Research

The motion data under two conditions were measured and recorded by a motion capture system (NOKOV, China) with eight cameras. We defined a whole gait cycle as the motions between two consecutive right heel strikes. At these moments, the marker on the right heel reached its maximum anterior position. Thus, the motion data recorded by the motion capture system were segmented into gait cycles. Based on the data, we calculated the mean angles of the hip, knee, and ankle joints on the sagittal plane in these gait cycles ranging from 0% to 100% in the two conditions, as shown in Fig. 9(a). As the position of the markers might unavoidably move relative to the subject between the two conditions, the imperceptible differences may have arisen as a result of marker repositioning errors. Even so, these differences highlight the minimally restrictive nature of the exoskeleton.

Citation Li H, Sui D, Ju H, et al. Mechanical compliance and dynamic load isolation design of lower limb exoskeleton for locomotion assistance[J]. IEEE/ASME Transactions on Mechatronics, 2022, 27(6): 5392-5402.

Link https://ieeexplore.ieee.org/abstract/document/9802513

Pitch angle sliding variance test method based on Mahony filter for zero-velocity detection

Keywords

ZVDT, Threshold judgment, ZUPT, Inertial navigation, Pedestrian navigation

Abstract

The threshold judgment method is a comparatively simple and classic zero-velocity detection (ZVDT) method for zero-velocity update. To solve the problem with the existing threshold judgment method, where the ZVDT effect is critically diminished by sensor noise, motion state changes, and other factors, this paper proposes a pitch angle sliding variance test (PSVT) method based on Mahony filtering. First, a Mahony filtering algorithm is designed to merge and de-noise the original foot acceleration and angular velocity information to provide high-precision pitch angle information. Subsequently, based on the significant periodicity, isolation, and characteristics of foot pitch angle variation during pedestrian movement, a PSVT method is proposed for pedestrian ZVDT. Experimental results show that for the motions of different pedestrians in different scenes, the average single-step misjudgment rate in the zero-velocity interval of the proposed method is less than 10% overall. When compared with the generalized likelihood ratio test, the ZVDT effect is improved by approximately 30%. The method effectively improves the applicability and accuracy of ZVDT for pedestrian movement, and will be significant in improving the applicability, navigational accuracy, and practical use of pedestrian autonomous navigation systems.

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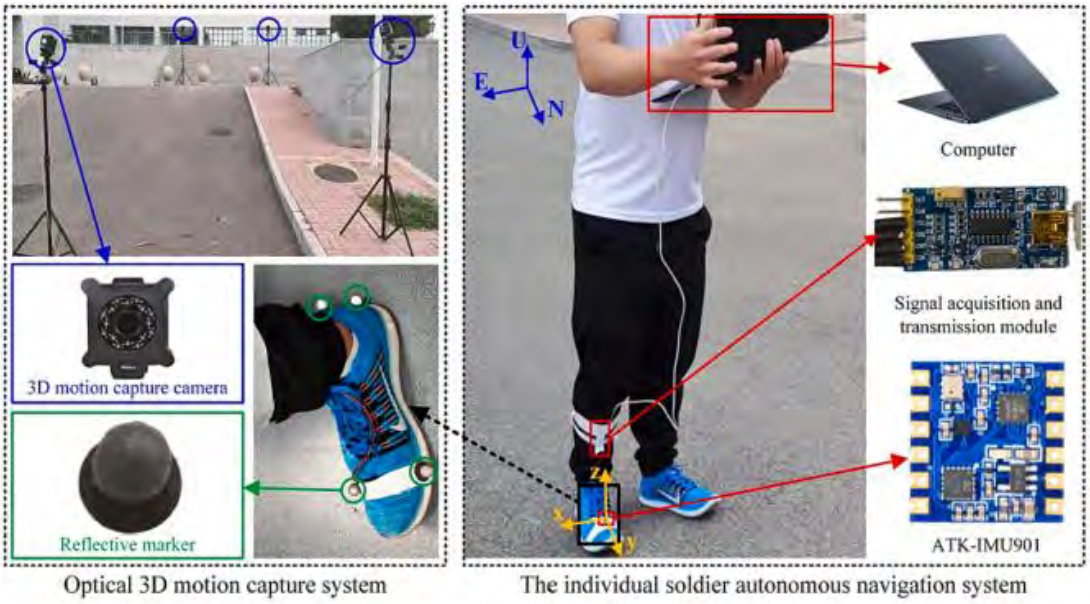

Fig. 6. Experimental device.

How NOKOV Contributes to the Research

During the experiment, the coordinate direction of the gyroscope and the accelerometer is right-forward-up, the right is the xaxis, the forward (toepointing) direction is the y-axis, and the vertical module outward direction is the z-axis, The attitude solution uses the east-north-sky coordinate system. In addition, we use an optical 3D motion capture system to acquire ground-truth references in experiments, which is the MARS2H for Beijing Nokov Science & Technology Co. , Ltd in China, and its 3Daccuracy can achieve + 0.15 mm.

Citation Yang Y, Zhao D, Liu W, et al. Pitch angle sliding variance test method based on Mahony filter for zero-velocity detection[J]. Measurement, 2022, 205: 112145.

Link https://www.sciencedirect.com/science/article/abs/pii/S0263224122013410

Positive Effect Study of a Passive Waist-Assistive Exoskeleton on Human Muscle Activity and Stability

Keywords

Mechatronics, Exoskeletons, Kinematics, Muscles, Market research, Stability analysis, Thorax

Abstract

Investigating effects of waist-assistive exoskeleton on human muscle activity and stability can not only help human to carry heavy objects easier and safer, but also promote the development of wearable robotic devices. To this end, this paper dedicates to studying positive impacts of a passive waist-assistive exoskeleton on human muscle activation and movement stability via experimental technology under carrying task. During the experiment studying, four subjects are recruited to carry different objects under three different tasks. The experimental results show that muscle activations of the left and right thorax thoracic erector spinaes of each subject are generally reduced around 10%. Also, the experimental results confirm that the root mean square (RMS) of the center of pressure (COP) of each subject is averagely reduced about 8% and movement trend of each subject's trunk has become smoother and more stable.

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(a) (b) (c)

Figure 3. Three different actions(a: bent 40°, b: bent 90°, c: semi-squat)

How NOKOV Contributes to the Research

Kinematic data are collected using an 8-camera, 3D video-motion analysis system (Nokov) with a sampling frequency of 50 Hz, which is shown in figure 5(c). There is a tip that the angles in these figures calculated by Nokov system are not explicitly the same as illustrated with the titles. These angles play a guidance role so that the phases can be divided more correctly.

Citation Huo X, Luo Z, Pang M, et al. Positive effect study of a passive waist-assistive exoskeleton on human muscle activity and stability[C]//2021 6th IEEE International Conference on Advanced Robotics and Mechatronics (ICARM). IEEE, 2021: 245-250.

Link https://ieeexplore.ieee.org/document/9536168

Simulation of Human Upright Standing Push-Recovery Based on OpenSim

Keywords

Musculoskeletal model, Human upright push-recovery, OpenSim, Stretch reflex, Short-range stiffness, Passive stiffness

Abstract

Investigating the human standing balance mechanisms under push-recovery task is of great importance to the study of biped robot balance control. Under human push-recovery mission, the passive stiffness, stretch reflex and short-range stiffness control mechanisms of human ankle joint are the main components in the internal mechanism of human body. To this end, this paper dedicates to evaluating the roles of the three aforementioned mechanisms during human upright standing push-recovery mission. Firstly, based on the simulation platform OpenSim4.0, this paper chooses a simplified lower-limb musculoskeletal model as the research object. Subsequently, this paper completes the design of the passive stiffness, stretch reflex and passive stiffness controller, and completes the static standing test and upright push-recovery simulation of the selected musculoskeletal model. Finally, in order to verify the effectiveness of the simulation, this paper uses electromyography, force plate and dynamic capture system to collect the relevant data of the human upright push-recovery. The experimental and simulation results reveal that the selected musculoskeletal model can basically simulate the process of human upright push-recovery under the joint actions of the three mechanisms noted above, which, to some degree, can reflect the effectiveness of the established method. Thus, the established method may provide some insights on the balance control of the bipedal robot.

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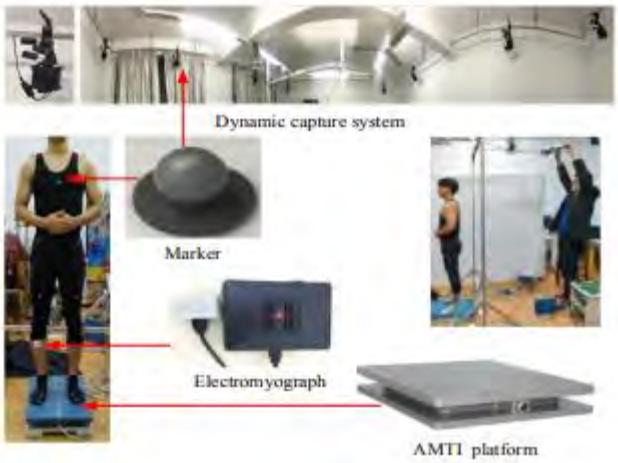

Fig. 4. Human upright push-recovery experiment

How NOKOV Contributes to the Research

The motion of the whole body is recorded in a NOKOV optical three-dimensional dynamic capture system with eight high-definition cameras at a frequency of 50 Hz. The sampling frequency of force plate and EMG is 1000 Hz. Since the time of human muscle reflex is very short, it is necessary to collect the relevant data of each system synchronously to ensure the timeliness of the experimental data. The preliminary scheme of this project is: through on-site guidance of different instructions, the use of real-time simulator to collect EMG data, force plate data and the TTL of dynamic capture system to achieve synchronization.

Citation Xiao T, Tang B, Pang M, et al. Simulation of Human Upright Standing Push-Recovery Based on OpenSim[C]//International Conference on Intelligent Robotics and Applications. Cham: Springer International Publishing, 2020: 308-319.

Link https://link.springer.com/chapter/10.1007/978-3-030-66645-3_26

WECMD: A multisensor dataset for wearable event cameras in the age of embodied intelligence

Keywords

Event camera, LiDAR, Wearable, Dataset, Pedestrian

Abstract

In the era of embodied intelligence, wearable datasets for pedestrian navigation are essential. However, publicly available multisensory datasets tailored to such scenarios remain scarce. Traditional sensors such as RGB cameras and LiDAR often struggle to capture the fast and irregular dynamics of human motion. To address this gap, we introduce a large-scale pedestrian-wearable dataset primarily recorded using event cameras. The dataset includes event camera, RGB cameras, LiDAR sensors, a tactical-grade IMU, and GNSS, covering a wide range of indoor and outdoor environments with diverse motion types and illumination conditions. High-precision ground truth is obtained using motion capture systems indoors and GNSS/IMU integration with bidirectional smoothing outdoors. The dataset is structured into 23 subsets categorized by motion dynamics and lighting, supporting the development and evaluation of robust localization and SLAM algorithms. Benchmarking with state-of-the-art frameworks reveals notable performance degradation under highly dynamic or low-light conditions, highlighting the dataset's value for advancing pedestrian navigation and event-based perception.

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Fig. 5. Indoor data collection scene.(A: Overall structure of the indoor dataset collection scene, B: Second floor scene of the indoor dataset with artificial building, C: Staircase scene of the indoor dataset with artificial building, D: First floor scene of the indoor dataset with artificial building)

How NOKOV Contributes to the Research

3.1. Sensor types in the WECMD dataset
In the WECMD dataset, the specific sensor types and their relative positions are illustrated in Table 2 and Fig. 3. The dataset primarily includes a tactical-grade IMU and a DVXplorer event camera with a resolution of 640 × 480 px, equipped with a 6-axis IMU. Additionally, the dataset contains two Flir RGB industrial cameras with a resolution of 1920 × 1200, along with the Livox Mid-70 and Velodyne VLP16 LiDAR. The compact Livox Mid-70 is mainly used in wearable devices, whereas the Velodyne VLP16 is deployed in outdoor vehicular scenarios. To collect high-precision ground truth data, we utilize a Nokov motion capture system for indoor environments, providing reference trajectories at 100 Hz with a spatial accuracy of 0.1 mm. For outdoor scenarios, we perform GNSS/IMU integration using GNSS signals from a Novatel receiver and data from a tactical-grade IMU, followed by bidirectional smoothing to obtain high-accuracy ground truth trajectories.

Citation Guo X, Wen Z, Huai J, et al. WECMD: A multisensor dataset for wearable event cameras in the age of embodied intelligence[J]. International Journal of Applied Earth Observation and Geoinformation, 2026, 146: 105019.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001646083500001

A Passive Backpack Exoskeleton Based on a Four-Bar-Sinusoidal Coupled Mechanism for Centroid Regulation and Load Reduction

Keywords

backpack exoskeleton robot, human-exoskeleton-load system, dynamics, kinematics, mechanisms and robots

Abstract

Excessive oscillation of the load centroid in the sagittal plane imposes impact and oscillatory force on the shoulders and back, contributing to upper-body muscle fatigue. To address this issue, this paper investigates a hip-driven backpack exoskeleton with a passive adaptive centroid adjustment mechanism, integrating a four-bar linkage with a sinusoidal mechanism to dynamically regulate the load centroid. Kinematics models of the human-load and human-exoskeleton-load systems are developed based on an extended six-bar representation, enabling comparative analysis of centroid trajectories. Dynamics models for the upper torso, single-leg, and double-leg support phases are constructed to evaluate pressure and joint torques variations. OPENSIM-based musculoskeletal simulations further analyze the torque distribution and metabolic activity of key gait-related muscles. Results demonstrate that the exoskeleton effectively reduces load centroid fluctuation and redistributes joint torques. Experimentally, it achieves an 85% reduction in peak load centroid displacement, a 49% decrease in total shoulder pressure, and a 50% reduction in lumbar swing amplitude during the single support phase. Simulations show lumbar and hip torque reductions of 52.68% and 23.64%, respectively, and a 32.85% decrease in erector spinae metabolic activity. This work addresses a gap in passive exoskeletons by introducing a rigid mechanism that adaptively shifts the load centroid without active control, verified through integrated modeling and experiment. It provides an effective strategy to reduce upper-body strain and improve gait efficiency during load-bearing locomotion.

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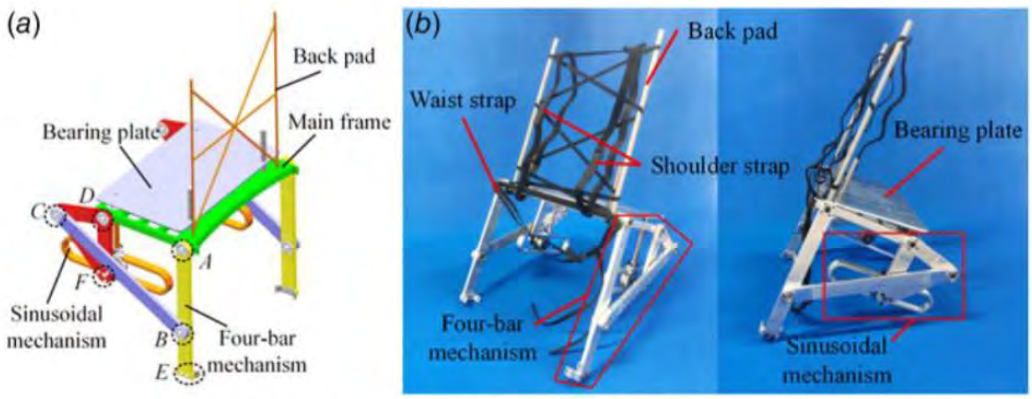

Fig. 2 Unpowered rigid backpack exoskeleton

How NOKOV Contributes to the Research

*Motions were measured by a reflective marker motion capture system (10 cameras, **Nokov, ** Beijing Metrology Technology Co., Ltd, China; 100 Hz). The reflective balls were placed according to the 39-point rule of the 2392 human model \[36]. In addition, a reflective ball was arranged on the backpack to obtain the load centroid. The total ground reaction force of the human and exo was measured by three force platforms (BP600900, Advanced Mechanical Technology, Inc., Watertown, MA; 90 * 60 cm; 100 Hz). The gross shoulder pressure was collected by two thin-film pressure sensors (M0303, CROWNTO, Luoyang Crown Extension Electronic Co., Ltd, China) as shown in Figs. 31(a) and 31(b).*

Citation Wei J, Ai C, Li X, et al. A Passive Backpack Exoskeleton Based on a Four-Bar-Sinusoidal Coupled Mechanism for Centroid Regulation and Load Reduction[J]. Journal of Mechanisms and Robotics, 2026: 1-15.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001709692900011

A wearable dual-IMU-based spatio-temporal fusion method for pedestrian inertial navigation systems

Abstract

To improve the accuracy and robustness of large-scale pedestrian autonomous navigation systems, this paper introduces a spatio-temporal information fusion method utilizing dual IMUs attached on the foot and waist. The proposed approach leverages the distinct periodic characteristics of waist motion to enhance the detection accuracy of zero-velocity observation periods for foot motion, thereby minimizing position drift. By capitalizing on the temporal and spatial consistency between different body segments during walking, the waist motion halfcycle is used as a substitute for the foot walking half-cycle, effectively reducing errors in step cycle detection. Additionally, the method adaptively determines the start and end points of the zero-velocity period by mapping the relationship among zero-velocity duration, walking speed and step cycle. This adaptive adjustment further refines the accuracy of zero-velocity corrections in inertial positioning. Experimental results demonstrate that the proposed method achieves a positioning error percentage of 0.46%, outperforming the traditional fixedthreshold method and adaptive-threshold method with an order of magnitude reduction in positioning error. Meanwhile, it also exhibits superior positioning performance in complex scenarios involving door opening and closing.

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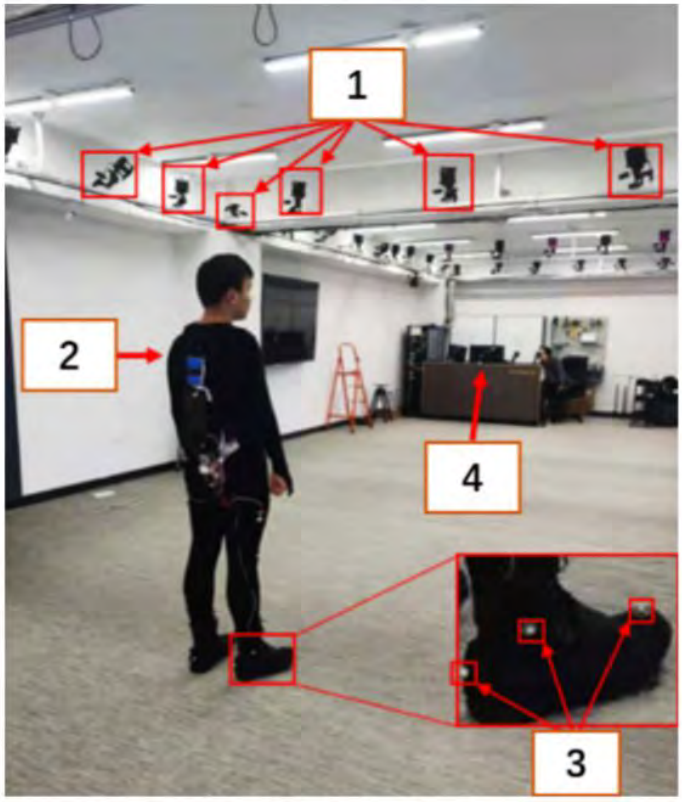

Fig. 5. Offline Zero-velocity model parameters calibration.

How NOKOV Contributes to the Research

In this section, the high-precision optical motion capture system, manufactured by NOKOV, is utilized for offline parameter calibration. This system employs multiple lenses to simultaneously capture reflective markers, enabling accurate tracking of the position and trajectory of moving objects. It provides precise position and velocity data with a localization accuracy of 0.1 mm, serving as a reliable reference for evaluating and analyzing pedestrian positioning performance. The experimental setup, including the configuration of the system and the experimenter, is illustrated in Fig. 5.

Citation Zhang Y, Huang S, Yang X, et al. A wearable dual-IMU-based spatio-temporal fusion method for pedestrian inertial navigation systems[J]. Measurement, 2026: 121357.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001735929200001

FreeTacMan: Robot-free Visuo-Tactile Data Collection System for Contact-rich Manipulation

Abstract

Enabling robots with contact-rich manipulation remains a pivotal challenge in robot learning, which is substantially hindered by the data collection gap, including its inefficiency and limited sensor setup. While prior work has explored handheld paradigms, their rod-based mechanical structures remain rigid and unintuitive, providing limited tactile feedback and posing challenges for human operators. Motivated by the dexterity and force feedback of human motion, we propose FreeTacMan, a human-centric and robot-free data collection system for accurate and efficient robot manipulation. Concretely, we design a wearable gripper with dual visuo-tactile sensors for data collection, which can be worn by human fingers for intuitive control. A high-precision optical tracking system is introduced to capture end-effector poses while synchronizing visual and tactile feedback simultaneously. We leverage FreeTacMan to collect a large-scale multimodal dataset, comprising over 3000k paired visual-tactile images with end-effector poses, 10k demonstration trajectories across 50 diverse contact-rich manipulation tasks. FreeTacMan achieves multiple improvements in data collection performance compared to prior works, and enables effective policy learning for contact-rich manipulation tasks with self-collected dataset. The full suite of hardware specifications and the dataset will be released to facilitate reproducibility and support research in visuo-tactile manipulation.

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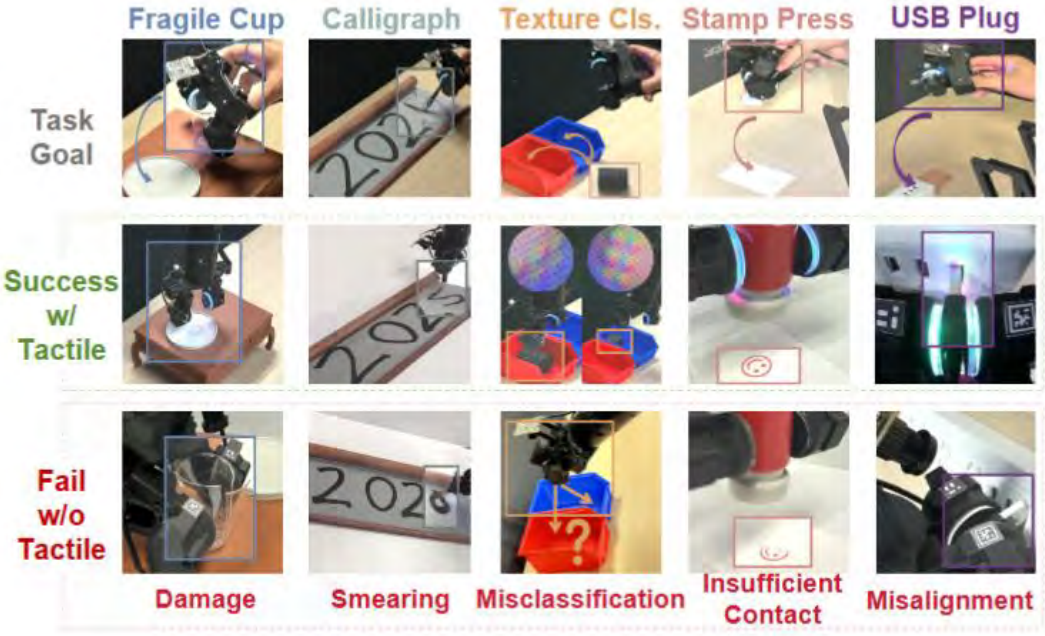

Fig. 5: **Human demonstrations and policy rollouts.** The top row shows goal trajectories, the middle row demonstrates successful rollouts with tactile feedback, and the bottom row showcases typical failure modes without tactile input.

How NOKOV Contributes to the Research

To facilitate human-to-robot skill transfer, a high-precision NOKOV Motion Capture System is used for 6D pose tracking of the interface at 240 Hz, achieving sub-millimeter accuracy. Five retro-reflective markers are mounted on the interfaces, with three positioned on the top plate to measure pose and two on the grippers to capture relative displacement. The coordinates of markers are first transformed from the world coordinate frame to the robot base coordinate frame.

Citation Wu L, Yu C, Ren J, et al. Freetacman: Robot-free visuo-tactile data collection system for contact-rich manipulation[J]. arXiv preprint arXiv:2506.01941, 2025.

Link

https://ev.publinks.top/app/doc/?docid=cpx_M4459111019817d323a0M7f661017816329

ML-guided self-powered biometric sensing in intelligent wearable devices

Keywords

self-powered biometric sensing system; machine learning; intelligent wearable devices; personnel identification; motion detection

Abstract

Intelligent wearable devices equipped with biometric sensing technology enable personnel identification, health management, activity recognition, and location tracking, thereby substantially improving quality of life. However, current devices face challenges in achieving a sustainable energy supply due to the inefficient energy conversion from low-frequency human motion. Furthermore, conventional biometric sensing methods relying on machine learning (ML) often struggle to balance between high recognition accuracy and rapid processing speeds. To address these challenges, this work proposes a self-powered wearable system integrated with a one-way electromagnetic harvester (OW-EH), which simultaneously enables energy harvesting and motion sensing. Employing an integral component extraction (ICE) ML model, the OW-EH device achieves effective recognition of personnel identities and associated motion patterns. Compared with conventional ML approaches, the ICE model improves recognition accuracy by 20.7% and reduces processing time by 54.12%, demonstrating its suitability for real-time wearable applications. Bench tests demonstrate that the compact OW-EH device generates an average power output of 206.5 mW, corresponding to normalized power densities of 3.40 mW Hz-2 cm-3 and 0.96 mW Hz-2 g-1. This output power level satisfies the operational requirements of typical portable electronics and supports self-powered navigation and triaxial acceleration monitoring during daily activities at speeds ranging from 4 to 8 km h-1. Notably, the system achieves a personnel identification accuracy of 95% and a motion detection accuracy of 90.39% using the ICE framework. Supported by ML, the OW-EH offers a sustainable and privacy-preserving solution for personalized biometric sensing, laying the solid foundation for digital twin systems to enhance intelligent living.

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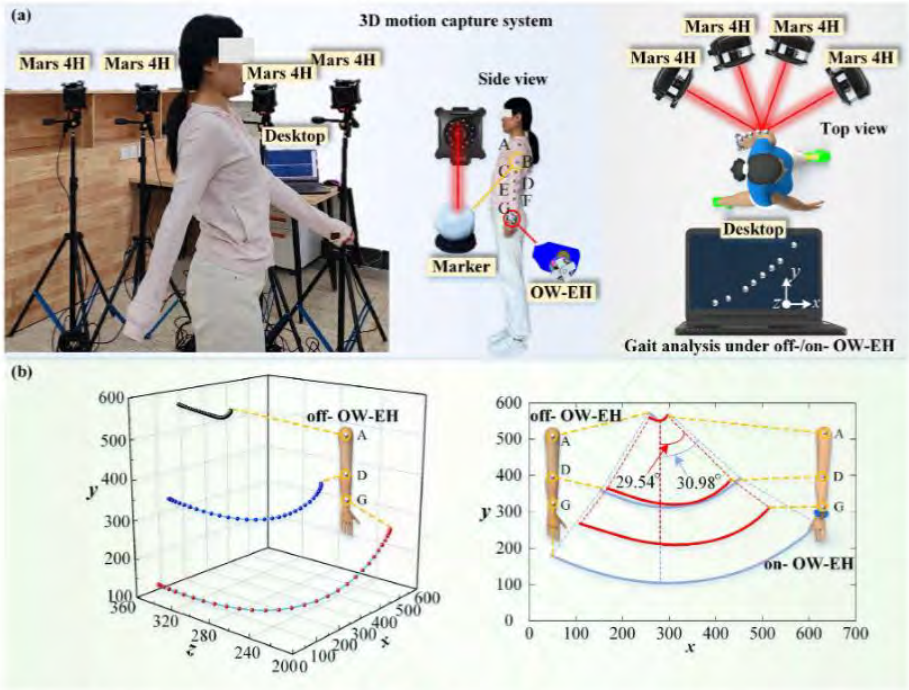

Figure 4 (Color online) Real-time gait analysis. (a) Experimental setup and procedure for gait analysis. (b) Three- and two-dimensional arm motions during slow walking with OW-EH on/off, demonstrating its minimal effect on human motion.

How NOKOV Contributes to the Research

> *3.1 Gait analysis\nTo analyze arm swing angles under different body motion conditions, an optical 3D motion capture system (NOKOV Mars 4H) was employed, as shown in Figure 4(a). The system accurately records the real-time 3D coordinates of marker nodes placed on the human body, enabling high-fidelity motion reconstruction and quantitative kinematic analysis.*

Citation Wang Z, Qiu H, Du H, et al. ML-guided self-powered biometric sensing in intelligent wearable devices[J]. Science China Technological Sciences, 2026, 69(7): 1720406.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001813640700001

Humanoid control of lower limb exoskeleton robot based on human gait data with sliding mode neural network

Keywords

STROKE REHABILITATION

Abstract

Lower limb exoskeleton robots offer an effective treatment for patients with lower extremity dysfunction. In order to improve the rehabilitation training effect based on the human motion mechanism, this paper proposes a humanoid sliding mode neural network controller based on the human gait. A humanoid model is constructed based on the human mechanism, and the parameterised gait trajectory is used as target to design the humanoid control system for robots. Considering the imprecision of the robot dynamics model, the neural network is adopted to compensate for the uncertain part of the model and improve the model accuracy. Moreover, the sliding mode control in the system improves the response speed, tracking performance, and stability of the control system. The Lyapunov stability analysis proves the stability of the control system theoretically. Meanwhile, an evaluation method using the similarity function is improved based on joint angle, velocity, and acceleration to evaluate the comfort of humans in rehabilitation training more reasonably. Finally, to verify the effectiveness of the proposed method, simulations are carried out based on experimental data. The results show that the control system could accurately track the target trajectory, of which the robot is highly similar to the human.

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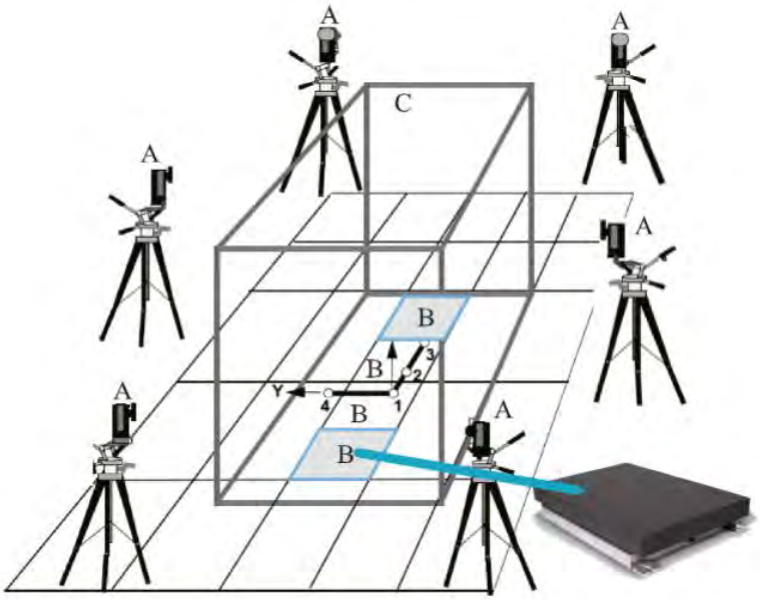

FIGURE 2 Typical configuration of the Nokov motion capture system. A—MARS cameras. B—Force measuring platform. C—Motion capture space

How NOKOV Contributes to the Research

In this paper, human gait data were gathered by a commercial motion capture system Nokov. This system can satisfy the most demanding requirements of the motion capture industry. As a real-time application, the results of the motion capture can be viewed instantly while simultaneously saved in several file formats. In addition, this software has a built-in set of tools to edit and process data in a graphical processing interface, without the need for additional software packages. System setup and calibration are fast and straightforward, with immediate feedback, a high degree of accuracy, and precision. The 3-D motion capture space based on experimental devices is built (as shown in Figure 2). During data collection, the calibrated system records the positional changes of the identified marker points in 3-D space with high precision and accuracy, while device B records the ground reaction force data simultaneously.

Citation Yu J, Zhang S, Wang A, et al. Humanoid control of lower limb exoskeleton robot based on human gait data with sliding mode neural network[J]. CAAI Transactions on Intelligence Technology, 2022, 7(4): 606-616.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:000837158300001

多自由度步态助力下肢外骨骼机器人的设计与分析

关键词

步态助力；下肢外骨骼机器人；光学运动捕捉；运动学；动力学

摘要

参照中国成年人体尺寸和关节特点，设计了一款多自由度步态助力下肢外骨骼机器人，利 用 SOLIDWORKS 完成三维实体建模。通过 NOKOV 光学运动捕捉系统采集受试者运动数据，结合 Mokka 和 AnyBody 处理获得关节角度。建立外骨骼机器人的空间 D-H 运动学模型，对末端姿 态进行正向求解。以矢状面角度特征为依据划分步态周期 8 阶段，分阶段建立人体矢状面 7 杆动 力学模型，利用拉格朗日法求解关节力矩，与 CGA 数据进行对比分析，并通过 ADMAS 对外骨 骼机器人模型进行动力学仿真分析。结果表明，多自由度步态助力下肢外骨骼机器人的设计具有 一定的合理性和运动平稳性。

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图 5　受试者步态数据采集

Fig. 5 Gait data collection of the subject

NOKOV 度量动作捕捉在研究中的应用摘录

通过 NOKOV 光学运动捕捉系统采集受试者运动数据，结合 Mokka 和 AnyBody 处理获得关节角度。建立外骨骼机器人的空间 D-H 运动学模型，对末端姿态进行正向求解。以矢状面角度特征为依据划分步态周期 8 阶段，分阶段建立人体矢状面 7 杆动力学模型，利用拉格朗日法求解关节力矩，与 CGA 数据进行对比分析，并通过 ADMAS 对外骨骼机器人模型进行动力学仿真分析。结果表明，多自由度步态助力下肢外骨骼机器人的设计具有一定的合理性和运动平稳性。

引用格式 周春国,孟奇,张璇栋,等.多自由度步态助力下肢外骨骼机器人的设计与分析[J/OL].机械科学与技术,1-8[2025-09-16].https://doi.org/10.13433/j.cnki.1003-8728.20250005.

链接

https://kns.cnki.net/kcms2/article/abstract?v=6h6U53PWxNR8peCf2AFGpXrQRNDR3ot8WR1hof3eHgXzApbWPL92QPAg28Wk7r_3-f1S4RN3lXf3ioZI0b4GOgc6GzZ6m53tfJX8gNQaITt0EtRsvLx9SDJ5_B-3CWsNm1m31dQD4FQKt5ZP_2joJ4yhwPd9N-_ZQUkJXlvDHYKZiiSGZaGsmzpbeQuuJgmm&uniplatform=NZKP

恒力悬浮背包动态卸荷技术研究

关键词

悬浮背包；恒力机构；可调阻尼；动态卸荷

摘要

随着科技水平的不断提高，可穿戴智能设备发展十分迅速。为减少人体在负重过程中的能量代谢，一系列提高人体运动能力的装备被研发出来。如外骨骼系统，通过主被动方式消除静态载荷对人体的影响，并且辅助关节运动进一步减少人体能量代谢。但是实际人体在行进过程中，由于负载与人体具有较强的耦合性导致运动过程中负载还会对人体产生惯性冲击，因此本课题主要针对在负重过程中产生的动态载荷对人体的影响，提出主被动结合的恒力悬浮背包装置。主要应用于单兵行军作战和科学考察等场合。详细论述了恒力悬浮背包的机械系统设计、可调阻尼系统设计、控制策略研究以及相关实验和结果分析。

通过现有悬浮背包的研究现状总结出目前存在的问题，即当负载质量和人体运动频率改变时系统悬浮效果都会有较大的变化。为此根据人体运动情况进行人体质心运动学建模和下肢等效建模，并结合传统悬浮背包进行耦合动力学建模和仿真分析，将其等效为简单的单质量弹簧阻尼系统和较为复杂的双质量弹簧阻尼系统，探究悬浮背包作用机理进而确定最佳工作状态。

在人机耦合系统动力学模型分析的基础上提出了基于弹簧式重力平衡原理的恒力悬浮背包。通过改变弹簧挂点位置来改变平衡负载的重量，该原理将系统刚度减小为 0，保证人体以不同频率运动时负载均处于悬浮状态。分析了恒力系统存在的误差，并设计了多滑轮补偿机构减少机械误差；对本体机械结构进行设计并对关键零部件进行有限元分析，采用拓扑优化进行轻量化处理；提出了基于电机发电模式下的可调阻尼系统，通过电磁继电器控制电机三相线通断改变系统阻尼。

为了提高恒力悬浮背包工作的安全性和稳定性提出了基于负载位置和相对速度的可调阻尼控制策略。采用 IMU 传感器实时检测负载的加速度并上传上位机记录，电机编码器读取背包负载位置及速度等信息并反馈给主控板 STM32F4，通过 PWM 形式动态改变系统阻尼的大小来调节负载的平衡状态，实现了低功耗的主动控制。

最后恒力悬浮背包系统装配集成，进行相关实验测试和结果分析。分别进行了恒力机构拉力测试，背包负载垂直惯性力测试、人体能量代谢测试以及机动性能测试。验证了恒力机构具有较好的平衡效果以及恒力悬浮背包具有一定的减负效果。实现自重 4kg，最大负载 25kg，平均减少动态载荷 88.45% 以上，在人体以 5km/h-9km/h 速度运动下均可正常工作的设计要求。

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图 2-3 动捕测试平台

NOKOV 度量动作捕捉在研究中的应用摘录

2.2.2 人体行走质心运动实验测试
为了验证该模型的准确性，采用动态捕捉设备测量人体质心的运动轨迹。设备采用的是NOKOV（度量） 光学三维动作捕捉系统。动态捕捉技术是随着计算机软硬件技术的发展和动画制作水平不断提高衍生出来的一种新技术，它主要包括传感器，即固定在运动物体特定部位的跟踪装置；信号捕捉设备，即常见的是高分辨率红外摄像机；数据传输设备，即将数据快速准确地传输到计算机系统进行处理；数据处理设备，经过系统捕捉到的数据经过修正处理后进行三维建模工作。

引用格式 巨浩天.恒力悬浮背包动态卸荷技术研究[D].哈尔滨工业大学，2021.DOI：10.27061/d.cnki.ghgdu.2021.002153.

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基于 GAN 的多维时间序列人体步态数据增强

关键词

生成对抗网络；多维步态数据；增强；下肢外骨骼机器人

摘要

典型的外骨骼机器人控制策略通常需要大量的人体步态数据来计算控制器的参考输入；步态预测或分类任务也需要大量的步态数据用于模型训练．数据增强技术可以合成与真实数据分布相似又保持原始数据动态特性的人工数据，从而降低人工收集步态数据的成本，有助于提高控制器的精度或模型的泛化能力．本研究以健康受试者在光学运动捕捉平台采集的原始步态数据为基础，通过建立多维和一维生成对抗网络模型学习真实数据的潜在分布从而生成相似分布的合成数据以达到一倍至数十倍增强真实数据的效果．对增强后的数据采用Ｔ－ＳＮＥ可视化、ＪＳ散度和ＭＡＥ度量两种数据的相似度，相比于一维时间序列ＧＡＮ模型，多维时间序列ＧＡＮ模型无论是从数据分布相似还是统计相似上精度都更高。

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图 1　步态动作捕捉平台

图 2　下肢外骨骼机器人

NOKOV 度量动作捕捉在研究中的应用摘录

本文所用的步态数据采用 NOKOV 三维红外被动式光学动作捕捉系统采集，其硬件设备主要由 6 台光学摄像机、多个 Mark 点、定位杆、校正杆、数据传输设备、采集软件等组成．摄像机左右各 3 个分两行排列，首先通过 L 型标定杆，T 型标定杆进行空间标定；标定的空间大小取决于人体贴点运动的空间范围，并调节适当的采样频率．步态数据采集时在人体的臀部两侧、两侧膝盖和两侧脚踝两侧共 6 处关节处贴上 Mark 点，人体在动作捕捉环境空间内运动时，当关节处的 Mark 点能够同时被 2 台摄像机捕捉到时即可记录下此刻 Mark 点的位置信息．Mark 点的空间坐标信息实时上传到采集软件，平滑处理之后保存为需要的数据格式．步态动作捕捉环境、关节处 Mark 点及后续研究用到的下肢外骨骼机器人，如图 1 和 2 所示。

引用格式 李志康，廖伍代，汪鑫等.基于 GAN 的多维时间序列人体步态数据增强[J].赣南师范大学学报，2021,42（06）：62-67.DOI：10.13698/j.cnki.cn36-1346/c.2021.06.013.

链接
https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C44YLTlOAiTRKibYlV5Vjs7iy_Rpms2pqwbFRRUtoUImHduDO6VtiX3CE8mpT1ZDgVBwU5NCW_mEzCaGwVrHxYTJ&uniplatform=NZKPT

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基于单M E M S 惯性传感器的运动追踪与轨迹重建

关键词

惯性传感器；运动追踪；轨迹重建；数据增强；运动分割

摘要

基于 MEMS 惯性传感器的运动追踪技术在可穿戴设备、无卫星导航等领域都有着重要的价值，然而目前还没有研究实现基于单个 MEMS 惯性传感器的任意轨迹实时重建任务，其原因在于轨迹重建过程中二次积分的计算会对传感器数据中的随机误差进行累计，最终导致轨迹重建结果严重失真。为此，设计了一款基于 MEMS 惯性传感器的可协同运动追踪模块，该模块内置数据增强算法，可有效降低传感器数据在轨迹重建任务中的随机误差。此外，为了减小二次积分过程中的累计误差，提出了一种基于智能运动分割算法的轨迹分段重建方案。实验结果表明，基于该运动追踪模块的轨迹重建方案可实现任意轨迹的精确还原。

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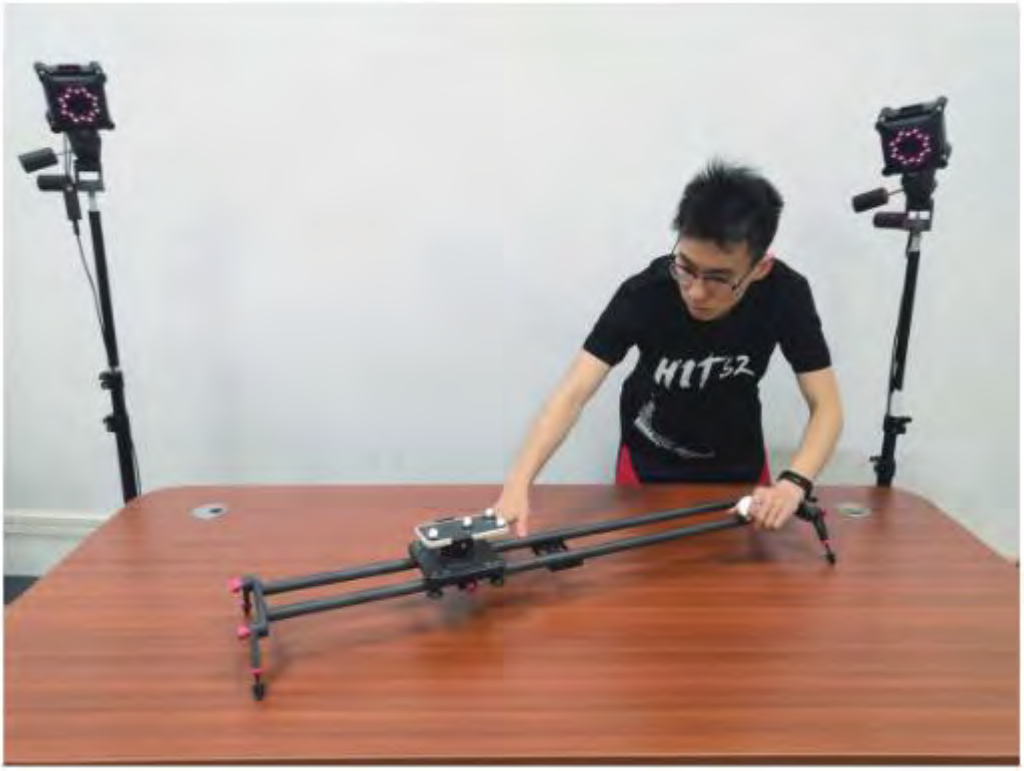

NOKOV 度量动作捕捉在研究中的应用摘录

借助光学传感器确定的运动分割点(方向剧变点)，采集物体运动的真实轨迹。借助光学传感器捕捉到的信息对惯性传感器原始波形中的分割点进行标注。通过对比光学传感器标注的数据分割点可以发现，该智能运动分割模型不仅准确地识别出了 62 个包含完整语义信息的手势动作，同时对每个动作起始与终止帧的位点检测也可以精确到个位。

引用格式 王一峰,赵毅.基于单 MEMS 惯性传感器的运动追踪与轨迹重建[J].传感技术学报,2022,35(10):1299-1310.

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基于动作捕捉的下肢外骨骼座椅稳定性评估

关键词

下肢外骨骼;稳定性评估;动作捕捉;坐姿;

摘要

通过比较和分析穿戴无源下肢外骨骼座椅前后保持不同坐姿时髋膝踝关节运动数据的差异和脊柱倾角的改变，定量评估外骨骼座椅的稳定性。招募 24 名受试者在不穿戴外骨骼和穿戴 A 型/B 型外骨骼的条件下完成规定的坐姿任务，采集运动学参数及主观评价。结果表明：外骨骼座椅对脊柱倾角和后倾坐姿任务中的运动数据影响显著，在前倾坐姿任务中运动学参数有所下降，其余任务中以上升趋势为主，使用 A 型外骨骼座椅后各关节运动数据的增幅高于 B 型；两款外骨骼均限制了躯干的活动范围，提升了脊柱前倾坐姿的稳定性，在使用后倾坐姿时稳定性较差，对其余坐姿的稳定性影响较小；存在局部不稳定的现象，整体稳定性有待进一步提高。主客观结果一致，表明该方法能有效定量评估外骨骼座椅的稳定性。

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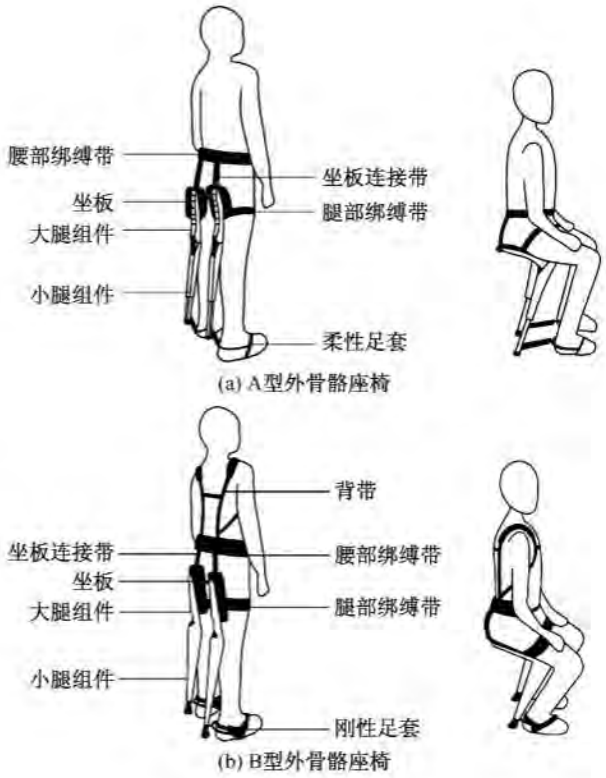

图 1　试验设备示意图

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> *1.2.2 光学动作捕捉设备*
> *选用 NOKOV 度量光学三维动作捕捉系统为本次试验的客观数据采集设备，采集区域共 8 个光学摄像头,采样频率为 60 帧/s。该系统可以追踪并记录皮肤表面反光标记点的位置，获得人体各节段运动数据。共 16 个点位,如图 2 所示。*

引用格式　文心雨,干静.基于动作捕捉的下肢外骨骼座椅稳定性评估[J].科技和产业,2025,25(17):27-36.

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基于惯性传感器的三维运动轨迹检测方法研究

关键词

小范围;惯性传感器;卡尔曼滤波;线性插值;运动轨迹;

摘要

针对人体微动作、手势识别等小范围内三维运动轨迹重建问题，采用惯性传感器检测方法。通过Zigbee 无线通信采集惯性传感器的加速度和角速度原始数据，并在 PC 端使用卡尔曼滤波预处理原始数据，利用四阶龙格库塔(Runge-Kutta)算法来更新旋转矩阵，从而积分求得位移并进行补偿得出轨迹，针对积分产生累积误差而导致运动轨迹不准确的问题，提出一种组合零加速度误差补偿算法，并且对运动过程中进行线性插值补偿，减少累积误差对小范围内检测运动轨迹的影响。实验结果表明，该方法能有效提高检测小范围内三维运动轨迹的准确度。

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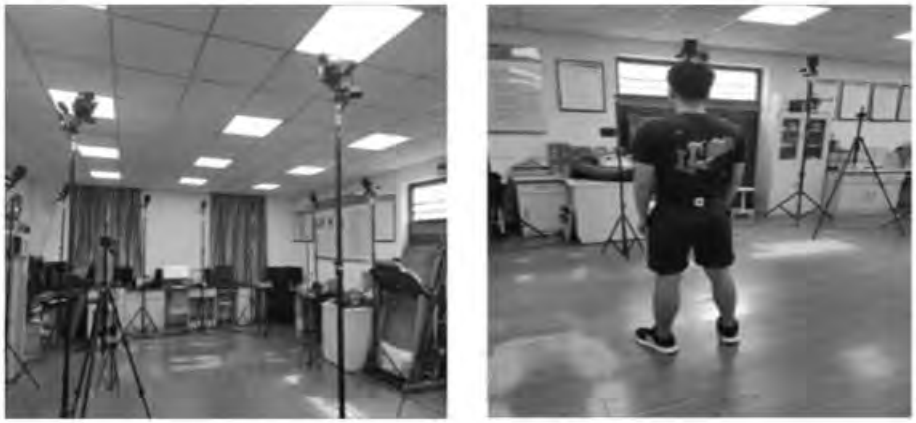

（a）动作捕捉镜头布置　　（b）传感器、标记点的位置

图 5　实验场景与设备

NOKOV 度量动作捕捉在研究中的应用摘录

3.2 实验 2
在室内环境中进行测试,受试者在腰部佩戴检测端设备,采用毫米级的 NOKOV 动作捕捉系统作为验证的参考系统,在测试区域周围共布置 12 个 Mars1.3H 型动作捕捉镜头(图 5(a)),采样率设置为 60 Hz,将光学标记点贴于检测端设备上(图 5(b))。

引用格式 杨焱,王伟,杨德伟,等.基于惯性传感器的三维运动轨迹检测方法研究[J].计算机应用与软件,2025,42(09):66-71.

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基于接触位置约束的交互式乒乓球运动辅助训练架构研究

关键词

位置约束;交互式;乒乓球;辅助训练;动作捕捉;

摘要

乒乓球运动作为一项广受欢迎的体育活动，对运动员的反应速度、手眼协调能力和技战术水平提出了较高的要求。然而，传统的训练方法在技术反馈的精准性和即时性方面存在局限，难以满足个性化和针对性训练的需求。因此，本研究提出了一种基于领域知识的乒乓球辅助训练框架，构建了结合接触位置约束与动作捕捉的乒乓球辅助训练架构。性能测试结果表明，相对无辅助训练架构、传统辅助训练架构，改进架构的下旋球接回球动作规范，分别提高了 86.57%、20.96%，且经改进架构辅助训练后的回球落点最为密集，受训者训练后的发球稳定性最高。最后，相比无辅助训练架构，使用改进架构下后的回球成功率提高了 22.03%以上。实验结果表明，乒乓球运动辅助训练模型具有良好的综合性能与应用效果，有效提高了受训者的训练效果，推动了运动训练的科学化和智能化发展。

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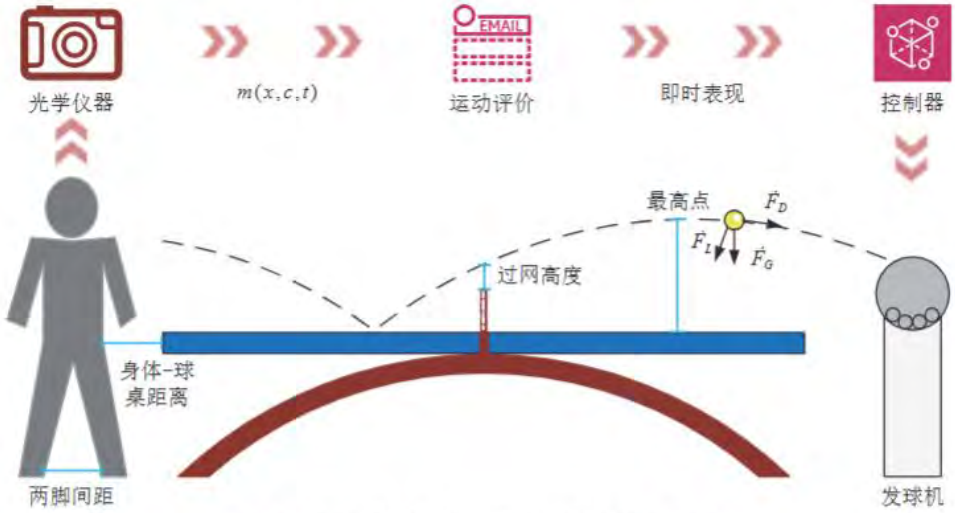

图 2　基于TACPC的乒乓球辅助训练示意图

NOKOV 度量动作捕捉在研究中的应用摘录

2 基于 TACPC 的交互式乒乓球运动辅助训练实验分析
为验证 TACPC 训练框架的有效性,首先搭建合适的实验环境,选取康博特发球机、Nokov 光学动捕镜头、Legacy 全身惯性动捕套装以及红双喜乒乓球与球拍。从某大学校内人员选取了 8 名 19-25 岁的乒乓球爱好者,受试者均具有不同水平的乒乓球训练背景,具体划分为四个等级,即新手级(无训练基础)初级(具有基本的训练经验)、中级(经常参加业余比赛)高级(具有专业训练背景)。为了保证研究结果的多样性和代表性,受试者被均匀地分配到两组,每组 4 人,且每组中各级别的数量均为 1 名。将两组分别在无辅助训练框架、传统辅助训练框架及研究所提出的 TACPC 训练辅助框架下进行训练测试。每组受试者的训练水平在实验开始前已通过预测试进行初步评估,并根据评估结果进行合理分组,以确保组间差异的最小化。在乒乓球训练中,组 1 和组 2 的受试者在接受训练前均穿戴动作捕捉套装,参与了不同辅助训练框架下的训练测试。受训者分别向对角位、中线边缘以及同侧边缘角这三个目标落点,各自成功接回 10 个球。这一训练过程涵盖了三种不同难度,即轻微上旋球、强上旋球、下旋球。每个难度下又设有三个不同的目标落点,每个落点需要接回 10 个球,总计每位受训者需完成 90 个接球,通过多次尝试以减少受训者因失误而带来的负面影响,提高结果的稳定性和准确性。首先以接回球的动作规范性为指标,使用三种辅助训练框架后的测试结果见图 4。

引用格式 程敏新.基于接触位置约束的交互式乒乓球运动辅助训练架构研究[J].集宁师范学院学报,2025,47(03):114-119.

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基于人体运动数据的下肢机器人运动学与动力学分析

关键词

外骨骼机器人；运动学；动力学；力矩；

摘要

针对有下肢运动障碍的患者，机器人系统与生物医学系统的结合为广大患者带来了福音，通过医学角度对人体运动数据规律的分析，可以更好地研发下肢外骨骼机器人系统。基于人体运动数据作为参考轨迹导入机器人系统的思想，通过三维红外式动作捕捉系统和三维测力平台系统实验采集人体下肢运动数据和足底力数据，利用算法对采集的数据进行滤波和拟合，通过建立下肢外骨骼机器人连杆模型，根据实验数据推导计算出髋关节和膝关节的转动角度和力矩曲线，基于Matlab 设计自适应控制器验证了基于实验数据的运动学和动力学分析的有效性，为下肢外骨骼机器人电机的选型和控制系统的设计提供了数据支持和理论依据。

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NOKOV 度量动作捕捉在研究中的应用摘录

人体下肢运动数据采集系统主要由动作捕捉和测力平台构成。动作捕捉使用 NOKOV 三维光学动作捕捉系统，包括红外动作捕捉镜头、反光标识(Marker) 、 动作捕捉软件和 T 型、L 型标定校正器等；红外动作捕捉镜头发射的红外线照射到反光标志点上后会被反射，镜头感应矩阵可接收反射红外线，多个镜头同时工作，即可确定标志点所在三维空间坐标；镜头的分辨率为 2048×1088，可以清晰地捕捉 Marker 点，捕捉频率可在 60~320 Hz 范围内根据需要进行调节，传输数据延迟时间较低，仅为 3. 2 ms。三维测力平台系统主要完成足底力学数据的采集，由两台测力平台、NK_Cortex 软件和 NI 数据采集卡等组成，三维测力传感器通过测量 x 轴、y 轴、z 轴 3 个方向上地面反作用力学数据，NI 数采集卡完成数据采集，通过 NK_Cortex 软件进行动力学分析；测力平台长宽高尺寸分别为 600 mm、400 mm 和 83 mm，采集数据具有较高的灵敏度，其分辨率可达到 0. 19 N/LSB，在 x、y 两轴的采集频率可达到 550Hz，z 轴方向上为 340 Hz；以上设备均可以满足较高水平的数据采集及分析。

引用格式 杜海龙，胡宁宁.基于人体运动数据的下肢机器人运动学与动力学分析[J].机械传动，2022,46（03）：128-134.DOI：10.16578/j.issn.1004.2539.2022.03.020.

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基于虚拟模型的下肢外骨骼辅助起立控制策略研究

关键词

起立运动；虚拟模型控制；躯干质心位姿；起立辅助外骨骼

摘要

起立是人们日常生活中使用频率最高的动作之一。生产活动中，工作人员常遇到负重起立的情况。现有研究大多以辅助行走为目标，较少考虑正常起立辅助。因此，分析人体正常起立过程，设计精确的起立控制算法，对起立辅助外骨骼的设计具有重要指导意义。

传统起立辅助主要通过位置控制实现。该方法虽然能够为穿戴者提供足够大的辅助力矩，但其对系统动力学建模的精度要求较高，且难以适应外界环境干扰。本文围绕人体起立过程中的位姿控制问题，基于虚拟模型控制设计外骨骼辅助起立策略，并从人体肌肉骨骼模型仿真和外骨骼辅助起立实验两方面验证了该方法的有效性和鲁棒性。主要研究工作包括：

（1）人体起立运动分析。首先通过分析起立过程中人体下肢各关节运动规律，建立人体简化模型，解析其运动学特性。然后，根据拉格朗日方程，推导起立过程的动力学模型，分析其力学特性。最后，在 OpenSim 软件中，建立人体肌肉骨骼模型，搭建起立仿真平台，为后续起立控制策略设计奠定基础。

（2）基于虚拟模型控制的外骨骼辅助策略研究。通过分析虚拟模型控制方法基本原理，构建基于人体躯干质心位姿的控制器。然后，搭建人体起立实验平台，解算躯干质心运动轨迹，并结合 OpenSim 正向动力学仿真技术和单纯形优化方法优化控制器模型参数。最后，基于优化结果，在仿真环境下对该控制方法的有效性和鲁棒性进行验证。

（3）起立辅助外骨骼设计。结合辅助负重起立需求，设计带有电机驱动的可穿戴式外骨骼装置，为穿戴者髋关节提供力矩。主要内容包括：机械结构设计、硬件平台搭建、控制系统设计三部分。基于前述仿真结果，确定外骨骼的虚拟模型控制策略。搭建外骨骼实验平台，以验证所提控制策略的实际效果。

实验结果表明，本装置可有效减轻臀大肌和半膜肌的肌肉激活程度，基于躯干质心的虚拟模型控制算法能实现人体从坐姿到站姿的稳定转换，并能够适应不同任务要求，可抵抗外界干扰，切实提高了外骨骼起立运动的控制性能。另外，本文设计的起立辅助外骨骼为髋关节提供力矩，在人体起立过程中起到助力和纠正运动轨迹的作用。因此，本文提出的控制方法和辅助装置能为人体起立的助力型外骨骼控制系统和机械结构设计提供一定的理论支撑和技术参考。

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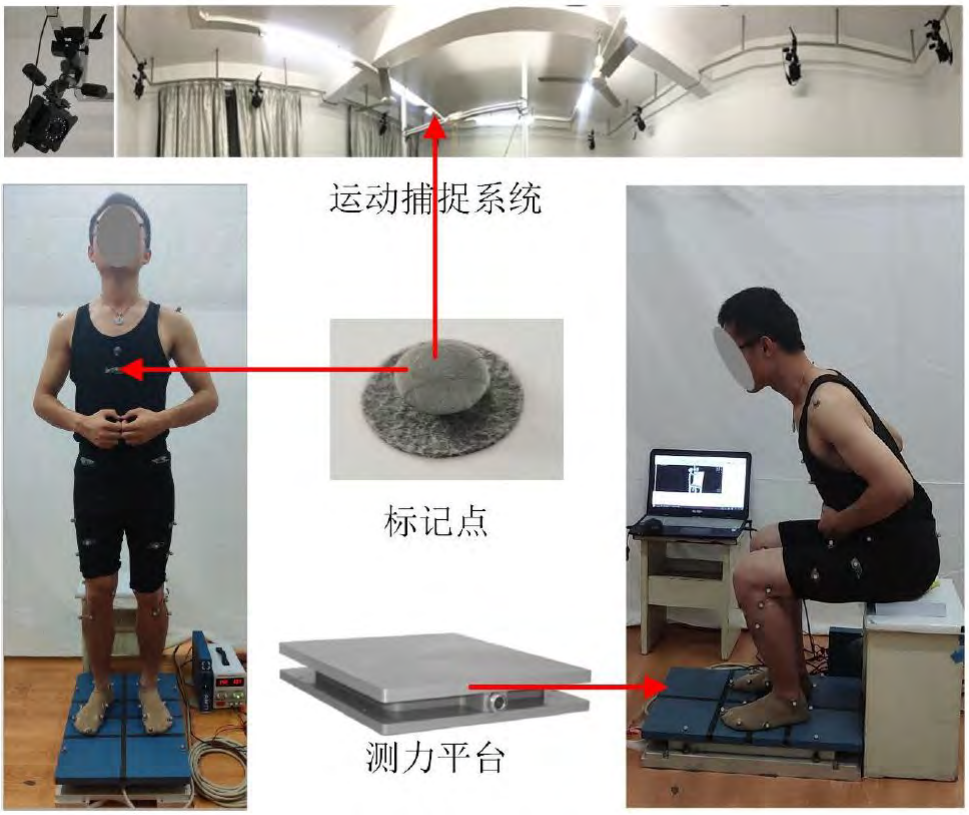

图 3-5 人体起立实验平台

NOKOV 度量动作捕捉在研究中的应用摘录

本次实验主要采用运动捕捉系统和测力平台采集人体起立过程中的运动学和动力学数据。其中，运动捕捉系统选用度量科技的（NOKOV，中国）光学三维动作捕捉系统。该系统主要由 8 台红外摄像头和若干个反光标志点（25mm）组成，采用高性能的摄像头捕捉被动发光标记点，构建三维数据的动作采集与分析系统。

引用格式 曾秋艳.基于虚拟模型的下肢外骨骼辅助起立控制策略研究[D].武汉理工大学，2022.DOI：10.27381/d.cnki.gwlgu.2022.000879.

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基于增强现实的人体运动中穿戴设备动态监控系统

关键词

动态监控系统;LSTM;注意力机制;步态轨迹预测;

摘要

对基于增强现实的人体运动中穿戴设备动态监控系统进行了研究，以篮球训练为例，提出了一种可穿戴设备动态监控系统，并设计了一种基于 LSTM 和注意力机制的步态轨迹预测模型，对运动员下肢的髋关节、膝关节和踝关节的角度进行实时在线分析，并获取运动员的步态轨迹预测结果。首先，对传统 LSTM 网络结构进行了研究与分析，然后搭建了基于 LSTM 和注意力机制的步态轨迹预测模型，随后对动态监控系统的整体框架进行了简单设计，最后对预测模型进行实验测试。测试结果表明：设计的基于 LSTM 和注意力机制预测模型的 RMSE 和 MAE 值明显低于基于传统 LSTM 预测模型，具有有效性，能够对运动员髋关节和踝关节的角度进行精准预测；基于 LSTM 和注意力机制的步态轨迹预测模型给出的轨迹预测结果，不论是从整体上看还是从细节上看，都与实际数据贴合地更好，几乎与真实的步态轨迹相重合，表明该模型的性能更好，更适用于设计可穿戴设备动态监控系统。

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NOKOV 度量动作捕捉在研究中的应用摘录

本次实验数据采集场地为一空旷的室内篮球场，共采用 12 个摄像机沿着篮球场边框布置，每一侧 3 个摄像机，随机选取 5 个运动员在篮球场内进行日常训练。
采用 NOKOV 红外被动光学运动捕捉平台对运动员的下肢髋关节、膝关节和踝关节三个部位的步态数据进行捕捉获取。

引用格式 杜前潮.基于增强现实的人体运动中穿戴设备动态监控系统[J].自动化与仪器仪表，2024（02）：140-144.DOI：10.14016/j.cnki.1001-9227.2024.02.140.

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https://kns.cnki.net/kcms2/article/abstract?v=6RIcORkFSJSrvOeaDTcUYzoc-t5oRrKKj0Ffc2AiwFXQ4rAi1JozK_d8ucNQYpGEEqH1jlTKzLnmctfs-Aksh8-5Owj-p8BlXKwmuHIZGpN-d88zc-iCGRv1uoBu_ln8&uniplatform=NZKPT&language=gb

结合动作捕捉的外骨骼座椅协调性评估

关键词

外骨骼座椅；动作捕捉；Wilcoxon 秩和检验；协调性评估

摘要

外骨骼座椅在工业中的应用日渐流行，但部分外骨骼座椅的协调性仍有待提高。为全面评估外骨骼座椅在动静态下的协调性，12 名受试者在穿戴和未穿戴外骨骼座椅的条件下，模拟了快递流水线作业的动静态任务。运用光学动作捕捉设备采集髋膝踝关节的运动数据，并使用 SPSS 对其进行 Wilcoxon 秩和检验，最后通过五级李克特量表问卷采集主观评估数据，验证主客观结果的一致性。结果显示，在动态行走任务中，双腿膝关节角均有所下降，髋膝踝关节的速度和加速度也呈现下降趋势，在快走时尤为明显；在静态坐姿下，臀部和大腿上侧易产生不舒适感，调整坐姿容易发生倾倒。结论，该外骨骼座椅的整体协调性较差，限制了各关节的运动；在辅助坐姿时，易产生不稳定感和不舒适感。主客观数据结果表现一致，该方法能有效地定量评估外骨骼座椅的协调性，为进一步优化提供定量参考。

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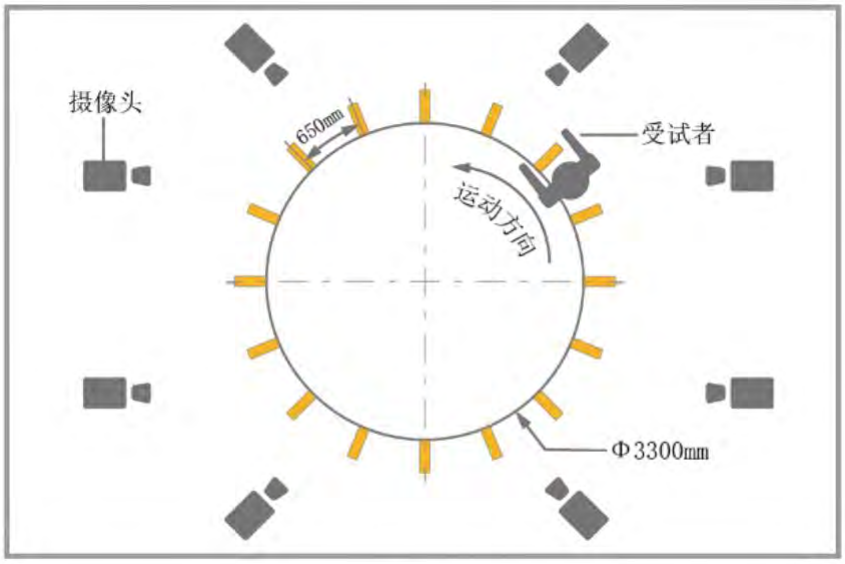

图 3 动捕场景示意图

Fig.3 Schematic Diagram of Motion Capture Scene

NOKOV 度量动作捕捉在研究中的应用摘录

动捕设备选用 NOKOV 度量光学三维动作捕捉仪，采集区域共安装 8 个光学摄像头，采样频率为 60 帧/秒。在受试者双腿外侧的髋关节、膝关节、踝关节、大腿中间和小腿中间粘贴 Mark 点，以采集双腿膝关节角角度和髋膝踝关节处的速度以及加速度变化，双腿共计 10 个点，如图 2 所示。
场地布置共 8 个摄像头，如图 3 所示，在捕捉区域每隔 65cm 标记黄线，围成环形测试区域。

引用格式 周针兵，干静，马静等.结合动作捕捉的外骨骼座椅协调性评估[J].机械设计与制造，2024（08）：237-241.DOI：10.19356/j.cnki.1001-3997.20240329.022.

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https://kns.cnki.net/kcms2/article/abstract?v=6RlcORkFSJTJsOFU-oTDSXYWZPCV3RpvRdXViVr3Or6MXqunrAe7wGK-pJlnuY7Vh9xVWqEcB0ZLcfYoYuDlQTPRPNn4oGfRu-YsaZraw3tbIJ4QLY76yg==&uniplatform=NZKPT&language=gb

可穿戴下肢外骨骼机器人多姿态运动特性分析与实验研究

关键词

可穿戴下肢外骨骼；外骨骼结构设计；运动仿真分析；重心稳定性影响；多姿态运动实验

摘要

随着人口老龄化现象不断加剧及运动障碍患者不断增多，越来越多的人需进行下肢辅助运动训练。手动治疗是目前最有效的方式，但手动治疗的医师数量有限且恢复周期较长，为了减轻医疗人员的工作压力，通过下肢外骨骼机器人对下肢有障碍患者进行辅助康复训练是一种有效途径。本文以下肢外骨骼机器人为研究对象，基于人体行走姿态运动实验采集数据，研究了人体下肢运动康复机理，设计了可穿戴下肢外骨骼机器人腰部与腿部可调节伸缩的机械结构，并对其进行了运动学、动力学分析，通过对下肢外骨骼机器人的多姿态运动分析，揭示了下肢外骨骼各关节的运动规律。主要研究内容如下：

（1）为了提高下肢外骨骼机器人的舒适性与协调性，对下肢外骨骼机器人髋、膝、踝等三个关节分别进行结构设计，提出了一种可穿戴下肢外骨骼的自适应长度调节结构，可实现不同人体的穿戴需求。通过三维动作捕捉设备对人体行走姿态进行了实验研究，采集了人体下肢髋、膝、踝等三个关节的运动姿态数据，揭示了下肢三关节的运动规律，为下肢外骨骼机器人三个关节的运动提供实验依据。

（2）利用 ANAYSWorkbench 对下肢外骨骼机器人进行静力学分析，验证了所设计的下肢外骨骼结构满足使用要求。基于 D-H 法与几何法，建立了下肢外骨骼机器人在蹲起、行走和上楼梯三种姿态下的运动模型；利用拉格朗日方程法，给出了不同姿态下的关节力矩方程；利用 ADAMS 对下肢外骨骼机器人在三种姿态下的运动学与动力学进行分析，得到了不同姿态时下肢三关节的位置、速度、加速度、足底作用力和力矩等关系曲线，总结了下肢外骨骼机器人的运动特性。

（3）基于 ZMP 双足投影多边形法稳定性判据，对下肢外骨骼机器人多姿态运动的动态稳定特性进行了研究，分析了多姿态运动的动态稳定特性，揭示了外骨骼机器人多姿态运动失稳机理。研究了重心对机器人稳定性的影响，通过建立重心 COG 与 ZMP 的倒立摆模型，得到 ZMP 与 COG 之间存在的空间位置关系。

（4）通过 Nokov 光学三维动作捕捉系统和测力平台搭建了下肢运动实验数据采集系统，采集人体蹲起、行走和上楼梯等姿态运动时下肢髋、膝、踝三关节的实验数据，对人体下肢三关节的位置、速度、加速度、角度、足底作用力及力矩等运动特性进行了深入分析，揭示了下肢三种姿态运动时的运动特性和下肢三关节的运动规律，为下肢外骨骼机器人的进一步优化设计提供了参考，为人机协同运动实验奠定了基础。

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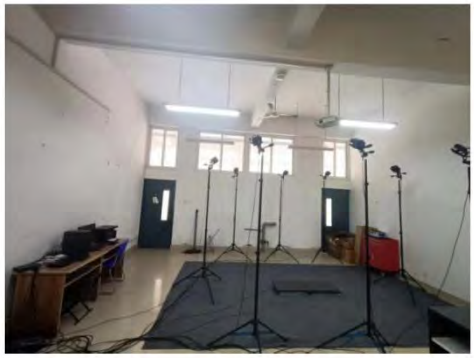
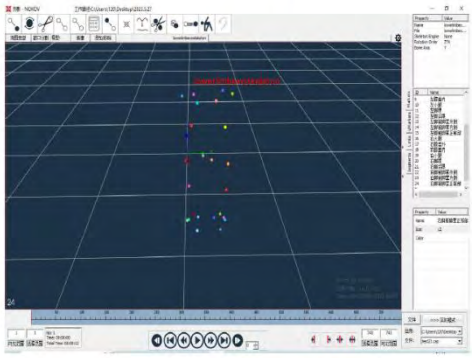
(a) 整体实验场地



(b) 实验摄像头布置

(c) 实验设备



(d) 软件显示及操作界面

图 2.5　Nokov 动作捕捉系统

NOKOV 度量动作捕捉在研究中的应用摘录

通过 Nokov 光学三维动作捕捉系统和测力平台搭建了下肢运动实验数据采集系统，采集人体蹲起、行走和上楼梯等姿态运动时下肢髋、膝、踝三关节的运动学与动力学实验数据，对人体下肢三关节的位置、速度、加速度、角度、足底作用力及力矩等运动特性进行了分析，研究分析了下肢三种姿态运动时的运动特性和下肢三个关节的运动规律。

引用格式　吴哲.可穿戴下肢外骨骼机器人多姿态运动特性分析与实验研究[D].烟台大学,2024.DOI:10.27437/d.cnki.gytdu.2024.000548.

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面向下肢外骨骼的多通道生物信息感知系统设计及其应用研究

关键词

下肢外骨骼；时间序列分析；步态评估；步态识别；长短时记忆网络

摘要

下肢助力式外骨骼是结合仿生、感知、控制等多项技术的综合性一体化系统，其在军事、医疗等多个领域展现出广阔的应用前景。实现人机一体化的耦合控制是目前外骨骼研究的一大难点，而人体步态的实时感知技术则是外骨骼精准控制的前提条件。文章以感知人体步态信息为出发点，设计并搭建面向下肢外骨骼的步态数据感知系统，并针对其在外骨骼中的应用场景展开研究：

（1）搭建步态感知系统并采集步态数据。针对传统单一传感器在步态信息获取中的局限性，本课题集成了表面肌电传感器、薄膜压力传感器、惯性测量单元 3 种不同种类传感器以搭建便携式、低成本的多源步态感知系统，并涵盖了基于 MATLAB 的数据存储、显示功能与基于蓝牙的无线传输功能以满足外骨骼使用需求。同时招募被试者采集了穿戴 3 款关节助力外骨骼样机的步态数据，以及 7 种不同动作模式的步态数据。

（2）面向无动力外骨骼的步态差异评估研究。现阶段外骨骼研发体系缺少对人体正常步态影响程度的评估方法以衡量其适用性。针对此问题，文章探讨了一种运用模糊算法分段步态数据，再结合动态时间规整（DTW）分析相似性的方法，以细化度量外骨骼步态与正常步态的差异，在对 3 款不同关节助力外骨骼样机的测试中得出，各关节助力外骨骼在步态不同阶段对人体关节、肌肉、足部活动都造成了不同程度不良影响。

（3）面向动力外骨骼的步态意图识别研究。动力外骨骼控制系统需准确、实时地识别人体步态以实现控制模式切换，为此文章搭建了基于 Bi-LSTM 的步态识别模型，得到 96.90%的离线识别准确率。同时设计了基于滑动时间窗口的在线识别机制并分析最优时间窗口。在此基础之上，文章探讨了基于角速度极值点检测的动态时间窗口调整方法，以实现兼顾准确性与实时性的步态在线识别，并设计在线识别实验，在 3 位被试者随机的步态切换中得到平均 94.44%的在线识别准确率，实验证明了该方法的有效性。

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图 1.4 步态分析系统构成

Figure 1.4 Gait analysis system

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1）三维动作捕捉系统：在人体佩戴反光标记物，并通过摄像头记录标记物运动轨迹以分析标记物在运动过程中的位置坐标变化，再计算出人体步态的时空参数，用于步态评估。常见的动作捕捉系统包括国产的 Nokov 系统。三维动捕系统也被称为步态分析的金标准。

引用格式 蒲贤. 面向下肢外骨骼的多通道生物信息感知系统设计及其应用研究[D].重庆大学,2022.DOI:10.27670/d.cnki.gcqdu.2022.002563.

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面向直立抗扰的踝关节外骨骼人机协作控制策略优化

关键词

人机协作控制；直立抗扰；人在环优化；踝关节外骨骼；

摘要

外骨骼可以为穿戴者提供身体支撑、保护、助力等辅助作用。穿戴者肌肉活动与外骨骼助力间的适应问题,是人机协作过程中的技术难题。本文以踝关节外骨骼为例,研究直立抗扰任务下的人机协作机制,探索简单任务下外骨骼人机协作控制的一般规律。

研究工作包括以下 3 个方面:

（1）设计面向直立抗扰的踝关节外骨骼。基于直立抗扰下人体平衡机理,建立踝关节力矩模型；通过"沙袋撞击"实验研究直立抗扰下人体踝关节运动特性,提供机械设计参数；外骨骼作动结构上,采用串联弹性作动器和鲍登绳驱动,避免外骨骼体积大、惯性大、抗冲击性差等问题。

（2）设计踝关节外骨骼力矩跟随控制的优化策略。采用三次样条曲线描述直立抗扰下外骨骼期望力矩；设计基于 PID 的外骨骼力矩跟随控制器；将穿戴者双腿肌肉激活量作为评估人机协作适应度的指标,建立人在环优化的目标函数；通过自适应粒子群改进算法,优化外骨骼期望力矩；获得最佳的力矩控制参数,实现直立抗扰下外骨骼人机协作最优控制。

（3）设计人机协作直立抗扰实验。采用实时控制器搭建外骨骼硬件控制系统；基于 Matlab 提供的 Simulink 工具包编写外骨骼控制程序；设计 3 组对比实验,评估基于优化的人机协作控制对穿戴者运动性能的改善的作用。实验结果表明:基于优化的踝关节外骨骼人机协作控制策略,可以有效的降低穿戴者下肢肌肉激活程度,减少穿戴者踝关节动作力矩,完成直立抗扰任务,对穿戴者有明显、积极的辅助作用。这为外骨骼人机协作控制的研究,提供了一种通用的解决方法。

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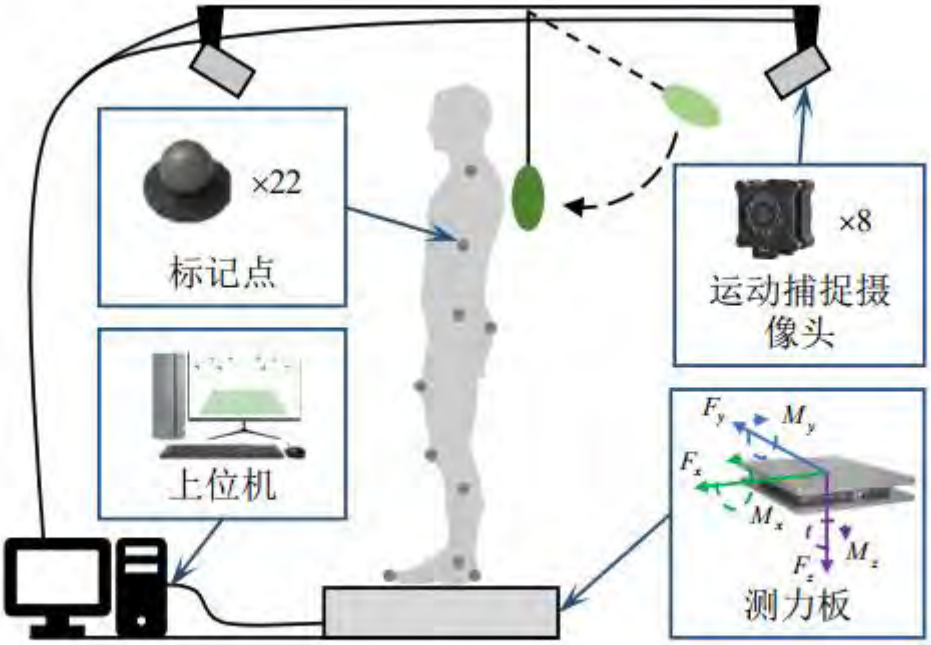

图 2-3　直立抗扰实验平台

NOKOV 度量动作捕捉在研究中的应用摘录

实验过程中，通过 AMTI 测力板和 Nokov 光学运动捕捉系统，采集受试者直立抗扰期间足底压力/力矩和关节运动角度信息，借助上位机软件（NetForce 和 NKCotex）实时解析、显示、保存各动态数据。因此，受试者需要穿戴附着反光材质标记点的紧身衣，站在测力板上进行"沙袋撞击"实验，如图 2-3 所示。

引用格式 曹雨阳.面向直立抗扰的踝关节外骨骼人机协作控制策略优化[D].武汉理工大学，2020.DOI：10.27381/d.cnki.gwlgu.2020.001530.

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人机耦合模型研究及其在下肢外骨骼机器人设计中的应用

关键词

外骨骼机器人；人机耦合模型；步态运动学；逆动力学；机器人设计优化

摘要

下肢外骨骼机器人用于辅助人体步态,减少人体能量消耗。对于下肢外骨骼机器人的研究,通常需要搭建模型探索原理和优化参数。本文提出了一种人体-外骨骼机器人的单元化建模方法,用于人佩戴外骨骼机器人情况下的运动学和动力学的计算,并将模型应用到外骨骼机器人的设计和控制优化上。

首先,利用单元化建模思路将人机耦合模型分解为单元和连接,将人体部位和外骨骼机器人单元化抽象,通过将牛顿-欧拉迭代方程改写为单元化的递推公式,从而完成人机耦合模型的运动学和动力学计算。通过触地点算法、虚拟足部、浮空阶段运动学算法和动力学初始化算法实现了模型在步态数据输入下的可解性。通过动作捕捉系统和测力板,对模型的运动学动力学计算结果进行了初步实验验证。

其次,基于模型对下肢外骨骼机器人进行了设计。通过对外骨构造区域进行数学化表达,结合寻优算法实现双被动外骨骼和四被动协同外骨骼的结构和参数设计。通过傅里叶级数对机电辅助力进行描述,结合寻优算法实现了踝关节机电外骨骼和髋关节机电外骨骼的输出力的控制曲线。

最后,对模型进行 java 编程,实现了模型的跨平台调用。通过标准库匹配的步态预测算法,结合机电外骨骼传感器和蓝牙通讯,实现了模型在安卓端的部署。搭建了被动外骨骼样机进行了被动外骨骼的减代谢实验。在髋关节机电外骨骼机器人设置输出力进行了机电外骨骼的减代谢实验。

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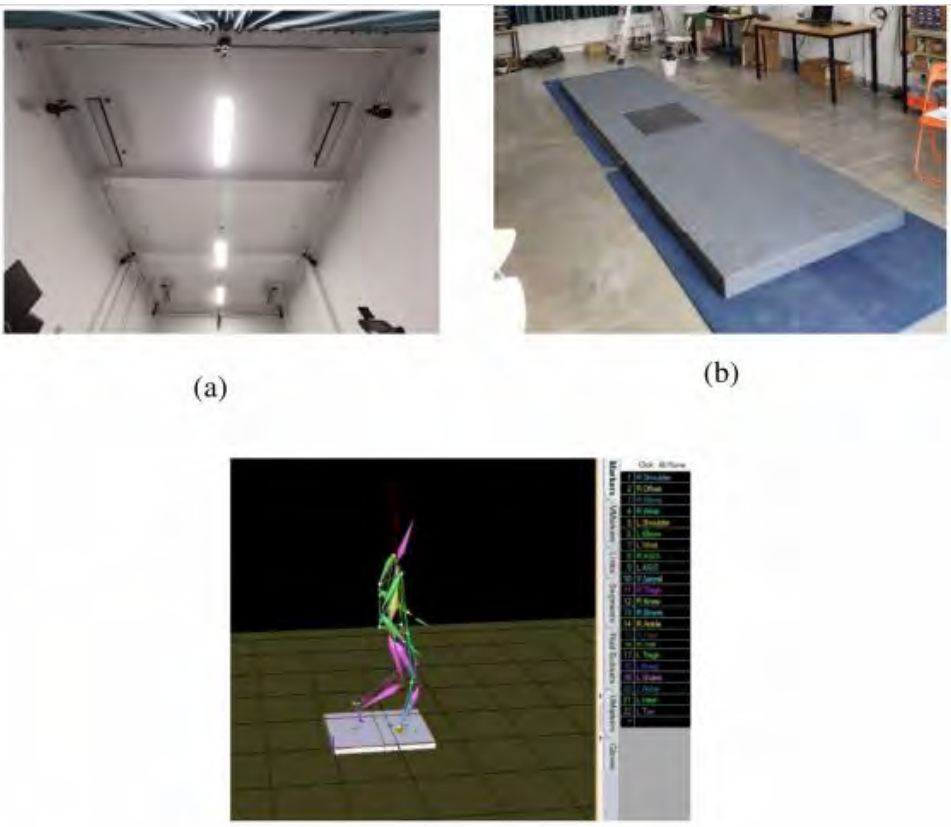

(a) (b) (c)

图 2-12 (a) Nokov 光学三维动作捕捉系统 (b)BERTEC 三维测力平台 (c) 标记点后处理软件

NOKOV 度量动作捕捉在研究中的应用摘录

实验环境如图 2-12 所示。其中，实验者身上贴有反射红外线的标记点在场地中行走，利用动作捕捉系统(Nokov 光学三维动作捕捉系统)解算出各单元的姿态并输入模型中，同时场地的两块测力板实时捕捉两脚的触地情况。将模型计算的双支撑阶段与测力板数据获得的双支撑阶段作对比。

引用格式 岳凡. 人机耦合模型研究及其在下肢外骨骼机器人设计中的应用[D].华南理工大学,2021.DOI:10.27151/d.cnki.ghnlu.2021.003977.

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人体膝关节外骨骼助力装置设计及实验研究

关键词

动作捕捉系统；动力学分析；膝关节外骨骼；平面涡卷弹簧

摘要

膝关节是人体下肢的中间核心关节，其结构的复杂性使得它成为最容易发生病变的关节之一。随着我国社会老龄化趋势的加剧，膝关节相关疾病的发病率也在不断攀升，这些疾病不仅给人们的身体带来疼痛与不便，更在心理层面对人们的健康产生负面影响。外骨骼装置作为一种新型助力系统可以有效降低膝关节载荷，降低其发病率。传统的外骨骼装置主要借助电机、气动和液压驱动等方式作为动力源，其使用成本高且结构臃肿不方便普通人使用。

对此，本文基于人体生物力学特性和步态规律提出一种无源膝关节外骨骼助力装置，利用人体的被动步态驱动弹性元件进行能量的存储和释放来对膝关节进行助力，同时使用棘轮棘爪机构对弹性元件的能量释放时机进行控制，以此来增强该外骨骼助力装置的实际适用性。主要研究内容包括人体的运动学和动力学分析、外骨骼助力装置结构设计、动力学仿真和实验验证，具体如下：

（1）基于解剖学原理的人体下肢运动力分析。本文采用 D-H 参数法构建人体下肢简化模型同时结合三维动作捕捉实验获取了膝关节运动学参数。在此基础上，使用拉格朗日动力学方程于 MATLAB 软件计算获取膝关节在一个完整步态周期过程中的力矩变化曲线。

（2）无源膝关节外骨骼助力装置结构设计。通过对比现有的储能元件，选取了接触型平面涡卷弹簧作为核心储能元件并根据人体力学特性对其进行了详细的参数设计。在此基础上，确定了膝关节外骨骼助力装置的整体结构设计，并对该系统的助力原理进行了详细分析。为保障该助力装置整体的安全性，采用 SolidWorks Simulation 模块对平面涡卷弹簧及其相关部件进行了静力学仿真分析，确认了该装置的安全性和可行性，从而保障了整体机构的稳定运行。

（3）ADAMS 仿真平台验证。为验证数学模型的准确性和外骨骼助力装置的可行性。本文通过 ADAMS 对人体简化模型进行仿真验证，并将获取的膝关节力矩曲线与基于拉格朗日方程理论计算获取的膝关节力矩曲线进行对比，验证了数学模型的有效性。在此基础上，进一步在对穿戴外骨骼助力装置的人体简化模型进行仿真模拟得出，在佩戴外骨骼助力装置后，在整个步态运动过程中膝关节的力矩曲线有明显下降的趋势，实现了对膝关节的助力效果，验证了外骨骼助力装置的有效性。

（4）基于实验平台的外骨骼助力效能评估。为验证本文设计的膝关节外骨骼助力装置的实际有效性，借助 3D 打印技术制作外骨骼样机并通过三维动作捕捉系统和表面肌电测试系统两大实验平台对人体穿戴外骨骼前后的膝关节力矩及屈曲肌肉群的表面肌电信号进行对比分析，最终验证了该装置在实际应用中的助力效能。

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图2-15 步态参数采集实验场地

Fig.2-15 Experimental site for gait parameter acquisition

图2-19 步态参数采集实验

Fig.2-19 Gait parameter acquisition experiment

NOKOV 度量动作捕捉在研究中的应用摘录

在本研究中，我们选用了 NOKOV 三维红外被动式光学动作捕捉系统，其核心镜头为 Mars1.3H 型号。这款镜头以其卓越的性能，确保了动作捕捉的精准性与可靠性。

引用格式 严亮.人体膝关节外骨骼助力装置设计及实验研究[D].西安理工大学，2024.DOI：10.27398/d.cnki.gxalu.2024.000067.

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人体膝关节助力与俘能装置研究

关键词

运动生物力学；步态分析；助力与俘能装置；运动学与动力学分析

摘要

人体膝关节助力与俘能装置是一种能够增强下肢肌肉力量和将下肢能量转化为电能的装置。通过与人机协同工作,该装置能够提高人体运动能量利用率,并回收能量以缓冲肌肉疲劳。此技术具有广阔的应用前景,包括军事应用、医疗康复、工业生产以及环境保护。本研究以膝关节助力与俘能外骨骼为研究对象,将装置分为助力和俘能两个部分,并基于人体下肢生物力学特征,对助力与俘能装置的结构进行设计创新。最终,通过仿真与实验验证,证明了该装置的有效性。主要的研究内容如下:(1)人体下肢步态数据采集。通过对人体下肢的生理结构和解剖学进行分析,从矢状面、冠状面和水平面上描述了人体下肢运动的特征,深入探究步态周期的运动规律。后续使用 NOKOV 三维动作捕捉系统对受试者的步态周期进行了测量实验,并使用 Origin 软件处理实验数据,以获得步态周期中人体下肢髋、膝关节角度变化参数。(2)膝关节助力与俘能装置创新设计。基于所获得的人体步态周期参数,分析人体下肢运动的能量转化过程,提出相应的下肢运动能量补偿及能量收集原理。通过比较现有储能材料,选择卷簧作为储能元件,结合实验验证压电材料的最佳俘能结构与连接方式。在此基础上,本研究对装置的助力结构与俘能结构进行创新设计,并对所设计的关键零部件进行了有限元分析,以验证安全性和可靠性。(3)膝关节助力与俘能装置运动学分析。基于下肢助力装置的三维模型,通过坐标法建立人体下肢简化模型,并利用拉格朗日运动方程建立人体膝关节助力与俘能装置的数学模型；结合公式法得到步态周期下的人体膝关节力矩变化矩阵。进而在 Adams 环境中进行助力性能仿真分析,通过数值模拟验证装置的可行性。(4)膝关节助力与俘能装置实验验证分析。通过采集佩戴实体样机前后人体行走过程中膝关节力矩、功率和做功数据,对比分析三组实验数据,研究发现在佩带装置后人体膝关节力矩曲线峰值下降,且分别节省了膝关节 22.21%、15.74%、13.22%的能量。此外,俘能实验表明受试者在佩带装置运动的条件下,测得在 200 ms 内压电均方根的峰值为 14.4 V,平均值为 10.1 V；在人体佩戴装置行走下可点亮 2 个串联的 3W LED 灯,并且亮度衰减较慢,在并联条件下,装置可点亮 13 个 3W LED 灯,但亮度衰减非常快；最终在步行实验中测得该装置的输出电压稳定在 4.68V,输出电流峰值为 0.3m A,功率峰值为 1.404m W。通过两种实验验证了装置的助力与俘能效果。本研究旨在设计和验证一种膝关节助力与俘能装置,研究成果为该装置的开发提供了一种可行有效的方法,为同类研究提供了有益的理论和实践指导。

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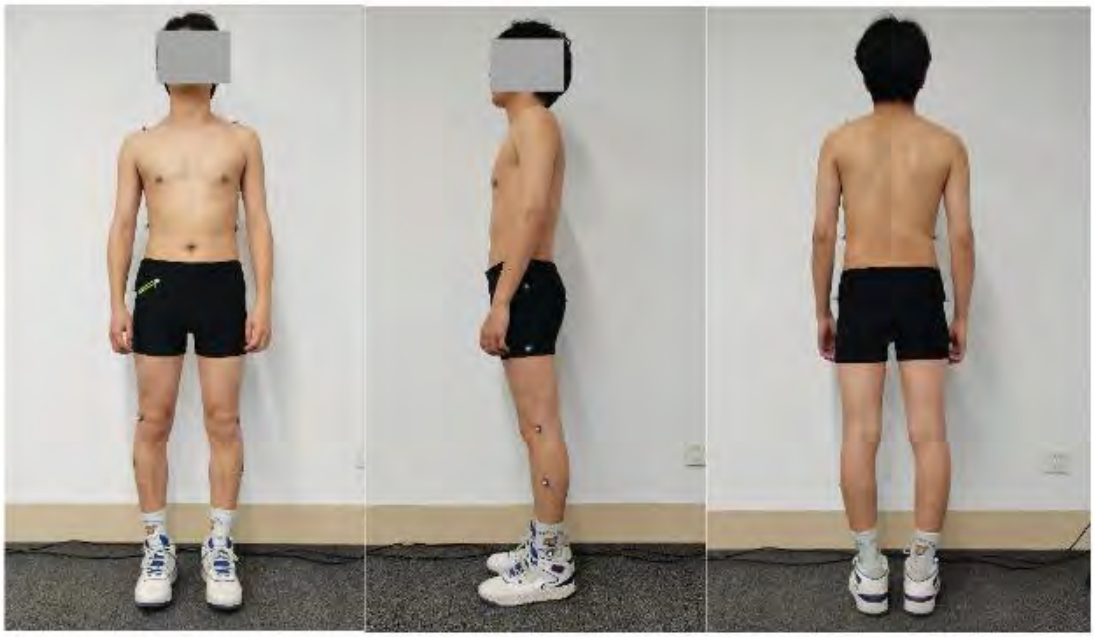

图 5-5 无佩戴装置贴点

NOKOV 度量动作捕捉在研究中的应用摘录

通过对人体下肢生理结构及解剖学的分析，从矢状面、冠状面和水平面三个平面上描述人体下肢运动特征，深入研究了人体步态周期的运动规律；通过 NOKOV 度量光学三维动作捕捉系统采集人体下肢关节运动角度，绘制了在步态周期内髋关节与膝关节的角度变化曲线，为后续的人体膝关节辅助与俘能装置提供设计依据，同时为建立人体下肢数学模型的计算与装置的仿真计算提供了基础数据。

引用格式 魏宇辰. 人体膝关节助力与俘能装置研究[D]. 西安理工大学,2023.DOI:10.27398/d.cnki.gxalu.2023.000439.

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适用于下肢助力型外骨骼机器人的步态分类研究

关键词

下肢助力型外骨骼机器人；步态分类；腰部步态信息；灰狼算法；支持向量机；

摘要

下肢助力型外骨骼机器人可帮助具有行走能力的穿戴者提高其运动能力或负载能力。然而,目前该类外骨骼尚不能根据穿戴者的当前步态自适应改变控制参数,导致助力效果不理想,舒适性较差。步态自适应控制是解决该问题的有效途径,但其难点之一在于如何通过佩戴在穿戴者身上的传感器信息进行准确地步态分类。传统步态分类研究是将大量传感器佩戴在穿戴者身上,通过大量收集各传感器信号中的步态信息来实现的。但此类方法对控制器性能要求非常高,导致设备成本的增加。此外,这种方法需要穿戴者佩戴大量传感器,导致佩戴舒适度的降低。因此,如何使用少量传感器的同时,又能准确地实时分类步态是一个亟待解决的关键问题。为此,本文提出适用于下肢助力型外骨骼机器人的、仅用腰部数据就能对 4 种常见步态进行有效分类的步态分类器,以减少传感器数量和步态信息数量。具体研究内容如下:首先,通过对行走步态的分析,确定以正常态、踢腿态、踏步态以及拖步态 4 种常见步态为分类对象。其次,采用 3D 运动捕捉系统对各步态时空参数和运动学参数进行采集,在通过对所采集数据进行计算和单因素方差分析的基础上,确定以腰部的 8 个步态信息作为步态分类器的信息源。最后,结合上述提取信息源建立基于灰狼算法优化支持向量机模型(GWO-RBF-SVM)的步态分类器。该分类器仅利用腰部 8 个步态信息就能对上述 4 种常见步态进行有效分类。实验结果表明所提出的步态分类器与其他分类器相比,具有更高的正确率、精确率、召回率和 F1 评分。

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图 3-2 实验空间

Fig.3-2 Experimental space

NOKOV 度量动作捕捉在研究中的应用摘录

本文采用 NOKOV 度量公司的 3D 运动捕捉系统(共 12 个摄像头)对 16 名 受试者进行步态数据采集，其采集频率为 60Hz。在此基础上，利用与硬件相 配套的 Seeker 软件进行步态三维信息的处理和导出。

引用格式 朴泓德. 适用于下肢助力型外骨骼机器人的步态分类研究[D].延边大学，2022.DOI：10.27439/d.cnki.gybdu.2022.001298.

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外骨骼助力行走状态检测与动力学控制方法研究

关键词

外骨骼；结构设计；状态检测；动力学建模；地面反作用力优化

摘要

外骨骼机器人是一种可穿戴式的机电设备,能够为穿戴者提供助力,提高穿戴者的运动能力,因此被广泛应用于军事、工业和医疗康复等领域,并逐步向民用普及。本课题设计的轻型行走助力下肢外骨骼系统主要用于增强穿戴者的下肢力量和运动能力,适用于负载行走等场合。本研究完成了下肢外骨骼系统的设计,针对系统状态检测和动力学算法进行了研究,并通过实验验证了算法的有效性,证明了研制的外骨骼机器人具有助力效果。基于对人体行走运动特点的分析,本课题设计的行走助力下肢外骨骼机器人采用了拟人化构型,设计了多连杆机构保证髋关节的轴心与人体对齐,采用了齿轮连杆组合机构实现膝关节瞬时轴心的跟随,保证灵活性和舒适性的同时,兼顾了外骨骼的轻量化。设计了基于 CAN 总线通讯的控制系统和由多个 IMU 组成的传感系统,满足实时控制和外骨骼数据采集要求,并且具有较高的可靠性。高精度的系统状态检测是解算动力学控制算法的基础。基于多点分布 IMU 传感器信息,实现了包括角度,角速度等状态信息量的解算,并基于 LTSM 神经网络,实现外骨骼检测角度到人体实际关节角度的校正,减小外骨骼与人体关节不对齐的影响。在无足底力传感器的条件下,分析了支撑相期间动力学无法求解的原因,建立了解耦动坐标系,实现了动力学建模。在该坐标系下,结合能量函数优化方法得到地面反作用力,解算关节力矩,实现外骨骼力矩控制。在上述研究的基础上,完成了外骨骼系统的装配和集成,并通过验证了算法的正确性。通过与动捕系统对比实验,验证外骨骼系统状态检测的准确度。通过与测力平台测量结果对比实验,验证地面反作用力优化算法的有效性。最后由人机交互力反映出外骨骼具有较好的助力效,能够达到降低能量消耗的目的。

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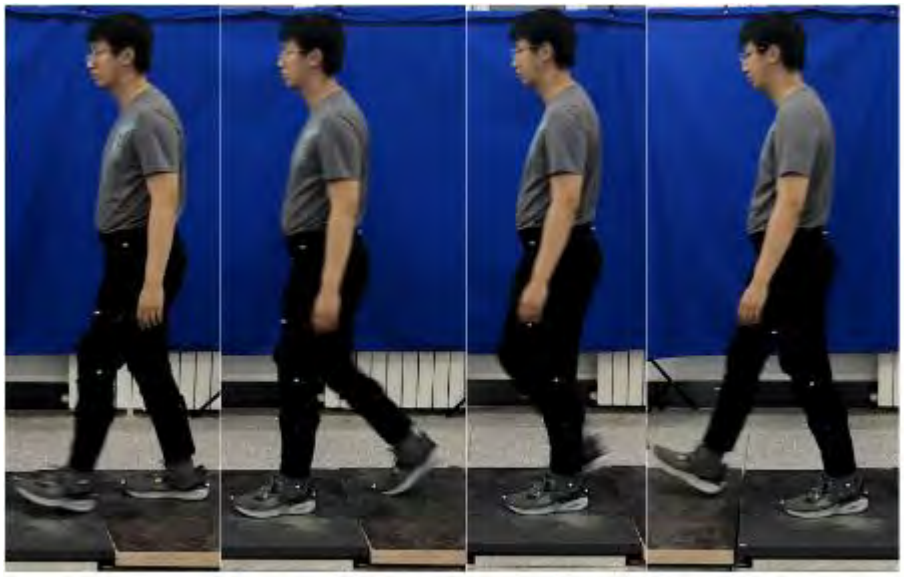

图 5-8　动力学算法实验过程

NOKOV 度量动作捕捉在研究中的应用摘录

为完成外骨骼优化得到的压力中心点和实际压力中心点的位置比较，需将人体坐标系与测力板坐标系进行对齐，因此本实验采用了光学动作捕捉系统。由于外骨骼系统状态检测实验已经证明外骨骼测量人体关节角度的准确性，而穿戴外骨骼会导致人体模型标记点被外骨骼遮蔽，因此本实验不穿戴外骨骼测试，关节角度通过动捕系统获取。通过在受试者身体上贴的标记点，重建人体运动模型，计算关节角度并将其输入到动力学算法中，验证地面反作用力优化结果，进而验证动力学算法效果。本实验使用 NOKOV 公司的 Mars1.3H 三维动作捕捉系统，其摄像头每秒可采集 60 帧图像数据，配套软件也可同测力平台联合使用，保证数据对齐。

引用格式　安一扬．外骨骼助力行走状态检测与动力学控制方法研究[D].哈尔滨工业大学,2022.DOI:10.27061/d.cnki.ghgdu.2022.003238.

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https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C475KOm_zrgu4sq25HxUBNNTmIbFx6y0bOQ0cH_CuEtpsH7iKx703w8YVio608WOWA0agxawFw7cqfNLuaT7CA5n&uniplatform=NZKPT

无动力髋关节助力外骨骼设计与分析

关键词

髋关节助力外骨骼；变刚度弹簧；逆运动学；逆动力学；仿真

摘要

为了提高现有助力外骨骼人机协同性，基于人体运动步态试验数据采集，建立人体下肢逆运动学、逆动力学模型，分析了髋关节行走时的角度、力矩、动势能等参数；根据相关参数分析，进行储能元件选型和设计，提出了一种储能元件为变刚度弹簧的无动力髋关节助力外骨骼；利用 Adams 开展了人机耦合模拟试验，验证了所设计外骨骼的人机协同性。模拟结果表明，所设计的无动力髋关节助力外骨骼具有较好的人机协同性。之后，进行外骨骼实物加工，开展了外骨骼穿戴试验。试验结果表明，穿戴外骨骼后，髋关节力矩在步态周期内平均减少 5.6%，做功平均减少 6.25%。以此证明，无动力髋关节助力外骨骼对人体行走有积极的助力效果。

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图26　实物模型穿戴效果图

Fig. 26　Wearing effect picture of the physical model

（a）动作捕捉试验行走过程正面　（b）动作捕捉试验行走过程背面

图27　穿戴试验行走过程图

Fig. 27　Wearing diagram of the experiment process

NOKOV 度量动作捕捉在研究中的应用摘录

为进一步验证该外骨骼的助力效果，进行了外骨骼的实物样机加工。图 26 所示为外骨骼的实物穿戴效果。穿戴外骨骼实物行走，并不会影响人体正常行走，外骨骼实物能够很好地贴合于人体髋关节和股骨上，在行走中有很好的人机协同性。之后，将所加工的外骨骼样机进行 Nokov 动作捕捉穿戴试验，验证了外骨骼的实际助力效果。
以步态周期为单位，分别让试验者进行穿戴外骨骼前后的平地行走试验。试验者在以相同步态周期为单位的前提下，控制相同的起点和终点进行穿戴外骨骼行走试验。图 27 为穿戴试验行走过程图。行走试验完成后，使用 Nokov 动作捕捉系统中的 Seeker 软件进行了试验数据的处理导出。

引用格式 杨洁，王旭鹏，唐欣尧等.无动力髋关节助力外骨骼设计与分析[J].机械传动，2024,48（08）：70-81.DOI：10.16578/j.issn.1004.2539.2024.08.010.

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无动力膝关节助力外骨骼设计及分析研究

关键词

膝关节助力；无动力外骨骼；动力学分析；人机耦合仿真

摘要

基于人机工程学和人体下肢步态运动特点的研究,本文提出了一种可以在膝关节处产生助力效果的无动力外骨骼装置。依据其在运动过程中通过弹性变形产生能量有即储存即释放的特点来进行运动助力,用来补偿下肢做负功期间的能量损失,实现降低人体代谢能量的目的,从而提高人体行走耐久性和负重能力。论文的主要研究工作和取得的成果如下:(1)膝关节助力外骨骼人体工效特征。基于解剖学原理对膝关节生理特性进行分析,基于 D-H 法建立下肢运动学模型并进行了生物力学分析,同时利用动作捕捉系统及三维扫描技术获得了膝关节相关参数,为后续装置设计奠定了基础；(2)膝关节助力外骨骼设计。综合考虑功能实现、使用安全性与可行性等因素,完成了膝关节助力外骨骼装置的储能单元选取、结构设计及重要零部件的有限元仿真；(3)动力学分析及人机耦合验证。基于拉格朗日建模方法,从系统能量角度构建了人体下肢的动力学模型并用 Matlab 求解了关节力矩；在 Adams 环境下输入外骨骼样机模型,通过仿真分析获得了关节力矩曲线。对比分析表明了所建立模型的正确性和样机设计的有效性；(4)膝关节助力外骨骼实验验证与分析。基于 3D 打印成型与机械加工,制作了膝关节助力外骨骼样机,利用 Nokov 动作捕捉系统与 Delsys 无线表面肌电测试设备进行实验,验证了外骨骼助力装置的有效性。

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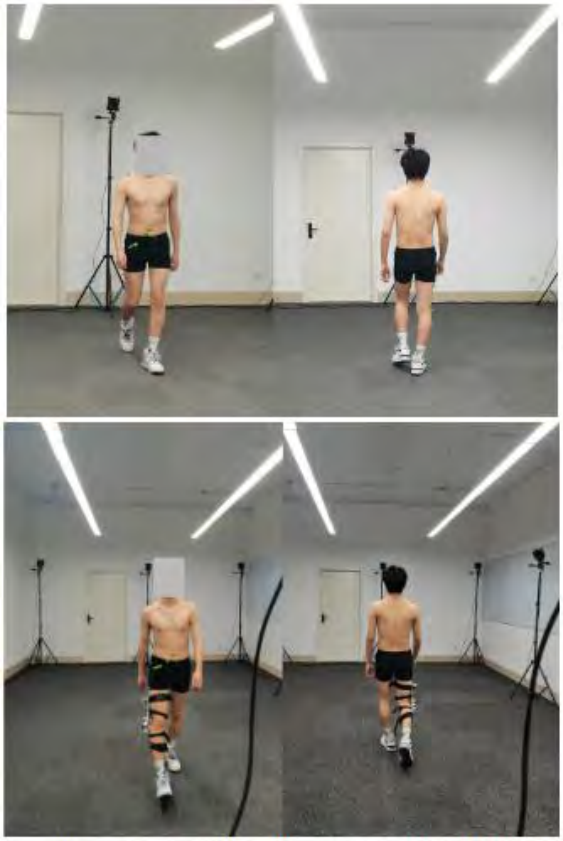

图 5-7 穿戴外骨骼前后运动捕捉图

NOKOV 度量动作捕捉在研究中的应用摘录

设计实验研究人体膝关节助力外骨骼装置的效能影响规律。为防止个体差异，综合考虑人体身高、体重、年龄、性别、体质指数（BMI）等对实验数据的影响变化。设置 NOKOV 度量光学三维动作捕捉实验与肌电检测两组实验从不同角度来进行外骨骼助力装置的效能验证。通过对比穿戴助力装置和未穿戴助力装置两种情况，获得下膝关节角度和膝关节力矩等参数进行评价，进而得出助力装置效果的实际结论，验证人体膝关节助力外骨骼模型的有效性。

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无动力型髋关节助力外骨骼设计与实验研究

关键词

髋关节；外骨骼；逆运动学；逆动力学；Adams 仿真；Nokov 实验

摘要

髋关节是人体活动中尤为重要的关节之一,在连接人体上半身的同时负责启动人体下肢。助力外骨骼是一种增强人体行走耐走性或减小人体代谢成本的辅助性行走设备,将人体自身行走的机械能进行回收,通过其机械结构将机械能转化为弹性势能,完成对人体行走提供助力,以此减小人体在行走过程中的的代谢成本,提升人体行走阈值。本文分析以髋关节为主的国内外无动力助力外骨骼现状,结合人体下肢运动特性和髋关节解剖学设计了一种储能元件为变刚度弹簧和卷簧的组合式无动力型髋关节助力外骨骼。主要研究内容如下:(1)人体下肢特性分析及数学模型建立。通过研究人体下肢运动生物力学特性和髋关节解剖学,建立人体下肢逆运动学模型和逆动力学模型,通过对人体进行下肢数据采集实验,得出躯干、足部位移轨迹,根据步态采集得到数据导入人体下肢逆动力学、逆运动学模型得到无动力髋关节助力外骨骼设计输入——髋关节运动参数。(2)无动力型髋关节外骨骼设计。通过分析人体下肢行走步态周期与髋关节的运动规律,得出装置适配运动原理,根据髋关节运动参数确定变刚度弹簧和卷簧的设计参数,通过 Ansys 仿真验证储能元件设计的合理性；根据变刚度弹簧运动行程设计凸轮传动机构与变刚度弹簧固定结构；根据人机工程学设计绑缚连接结构。最后进行外骨骼的实物加工,验证外骨骼机构设计的合理性、机械结构伟动性、人机协同性。(3)人机耦合仿真验证。利用 Adams 软件和 Sol idworks 构建人体与外骨骼的人耦合模型,在 ADAMS 中进行人机协同性和外骨骼助力效果分析,通过对比人体模型穿戴外骨骼前后的角速度、大腿质心速度、小腿质心速度来验证人机运动协同性；对比人体模型穿戴外骨骼前后的髋关节力矩,验证外骨骼设计的合理性及助力效果。(4)实验验证助力效果。通过 Nokov 动作捕捉实验,得出穿戴外骨骼前后髋关节角度、力矩、动能、势能的变化；通过肌电信号实验,得出穿戴外骨骼前后人体股直肌、股外侧肌、胫骨前肌的肌电信号变化,分析验证装置的助力效果。

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图 5-8 穿戴实验过程图前

图 5-9 穿戴实验过程图后

NOKOV 度量动作捕捉在研究中的应用摘录

通过 Nokov 动作捕捉实验，得出穿戴外骨骼前后院关节角度、力矩、动能、势能的变化；通过 1 肌电信号实验，得出穿戴外骨骼前后人体股自肌、股外侧肌、胫骨前肌的肌电信号变化，分析验证装置的助力效果。

引用格式 杨洁. 无动力型髋关节助力外骨骼设计与实验研究[D]. 西安理工大学,2023.DOI:10.27398/d.cnki.gxalu.2023.001338.

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无源上肢外骨骼的基础协调性评估

关键词

外骨骼；动作捕捉；协调性评估；运动平面；

摘要

外骨骼能为人类运动提供辅助力，辅助人们完成更高强度的工作，在市场中的应用日益增加，解决其人机协调性问题变得尤为重要。为评估无源上肢外骨骼在三个运动平面上的基础协调性，12 名受试者模拟了 3 种基础负重任务。运用光学动作捕捉设备采集受试者肩肘腕关节、腕肩髋的夹角和两肘间距的运动数据，并使用 SPSS 对其进行 Wilcoxon 秩和检验，最后通过五级李克特量表问卷采集主观评估数据，验证主客观结果的一致性。结果显示，该上肢外骨骼对水平面任务的干扰较为明显，会限制双臂水平向后摆动；对其余运动平面的干扰较小，不影响任务的正常完成。该外骨骼的协调性有待进一步提高，主客观结果一致，表明该方法能有效的定量评估外骨骼的协调性。

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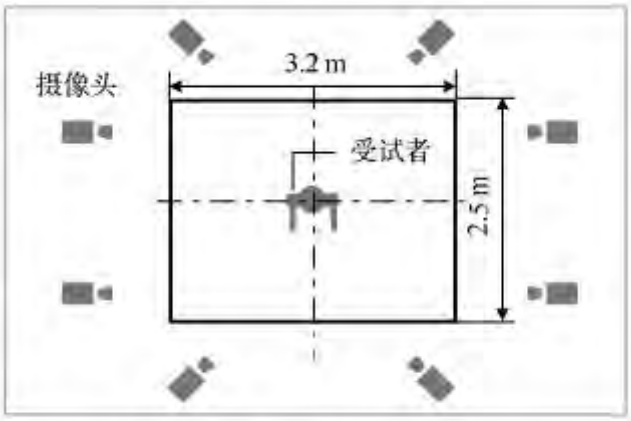

图 4 动作捕捉场景示意图

NOKOV 度量动作捕捉在研究中的应用摘录

选用 NOKOV 度量光学三维维动作捕捉仪作为本次实验的客观数据采集设备，采样频率为 60 帧/s。在受试者双侧的肩关节节、肘关节、腕关节和髋关节粘贴 Mark 点，以采集两肘间距的变化、双侧腕肩髋的夹角数据和双侧肩肘腕关节处的速度以及加速度变化，共计粘贴 8 个点，如图 3 所示。

引用格式 周针兵,干静,文心雨等.无源上肢外骨骼的基础协调性评估[J].机械,2022,49(04):74-80.

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下肢穿戴式助行器结构设计与仿真分析

关键词

下肢穿戴式助行器；下肢运动机制；动作捕捉实验；运动学建模；运动学仿真

摘要

设计了一款下肢穿戴式助行器，主要作用是辅助脑卒中、偏瘫等有下肢运动障碍的患者进行日常行走活动。首先，在对下肢运动机制、关节结构以及自由度组成分析的基础上，建立了下肢穿戴式助行器的三维结构模型；应用三维红外动作捕捉系统采集正常人行走步态数据，拟合出对应关节角度曲线；建立助行器简化 D-H 模型，对助行器进行了运动学建模分析；将动作捕捉实验（简称动捕实验）采集的步态数据作为仿真驱动，对助行器进行了运动学仿真验证。结果表明，仿真得到的关节角度变化曲线与实验采集到的角度曲线基本一致，角速度变化曲线与踝关节质心位置变化曲线符合正常人体行走规律，验证了下肢穿戴式助行器的结构设计的合理性。

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（a）反光标识球（Marker球）　　（b）高性能红外摄像机

图5　实验所用设备

Fig. 5　Equipment used in the experiment

（a）实验者左腿 Marker 球粘贴位置　　（b）实验者右腿 Marker 球粘贴位置

图6　实验者 Marker 球粘贴的位置

Fig. 6　Paste position of the experimenter Marker ball

NOKOV 度量动作捕捉在研究中的应用摘录

采用 Nokov 三维红外动作捕捉系统来进行动作捕捉实验，实验目的是采集正常人行走时下肢各个关节的点位数据，该数据可用作下肢穿戴式助行器运动仿真的驱动函数。该动作捕捉系统采用高性能的红外摄像机来获取被捕物体的三维坐标。在人体身上不同关节部位放置反光标识球（Marker 球），并通过反光原理精确捕捉这些 Marker 球的三维空间位置；然后，利用配套的控制软件对采集的数据进行一系列处理，即可得到能够使用的人体步态数据。实验中用到的反光标识球及 8 台高性能红外摄像机如图 5 所示。

实验结束后需要对采集到的数据进行观察处理，主要采用配套的 Nokov 软件平台；经过一系列处理，即可得到可供使用的步态数据。软件的工作界面如图 7 所示。

引用格式 王新，鄢沛峰.下肢穿戴式助行器结构设计与仿真分析[J].机械传动，2024,48（04）：95-102.DOI：10.16578/j.issn.1004.2539.2024.04.013.

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新疆高校体育教师数字化教学能力的困境与纾困之道

关键词

体育教师;数字化教学;新疆高校;

摘要

数字化体育教学是指师生在数字化环境下,利用多媒体、计算机、网络等数字技术,对体育知识和内容进行数字化处理,在体育教学实践中,如健美操、网球 3D 数字模拟教学等,是信息技术与高校体育课程整合的实践过程。随着社会的更迭发展,中共中央、国务院提出至 2035 年,教师需立足于学科前沿开展教学与科研活动,创新教学模式与方法,实现数字化对教师发展赋能的常态化,进一步实现教育现代化和教育强国的发展目标。新疆地区教育事业的发展对社会稳定、经济结构转型、文化传承、教育公平以及国家战略的实施具有深远意义和价值。教育于铸牢中华民族共同体意识进程中始终发挥着极为关键的作用。本研究通过文献资料法、实地考察法、逻辑法等研究方法,识别出新疆高校体育教师运用数字化教学的优势,深入分析新疆高校体育教师在数字化教学能力提升过程中所面临的现实困境,并基于上述困境提出相应的策略以增强教学能力。鉴于数字化教学的显著优势以及新疆地区实施数字化教学的现实困境,本文认为体育教师应致力于提升自身的数字意识,掌握数字技术知识与技能,促进专业发展,并加强数字技术知识与技能的学习应用。同时,国家、社会及学校层面应构建相应的激励机制及设备支持,促进体育教师在数字化教学能力方面的持续发展。旨在促进体育教师数字化教学能力提升,有效推进教育现代化进程,构建与现代化社会相适应的教育体系。

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NOKOV 度量动作捕捉在研究中的应用摘录

4.4 加强数字技术在教学中的应用
进阶阶段主要进行操作性学习，将基础阶段掌握的相关知识应用于实际操作。教学前，通过学生基本身体素质、学习能力及运动等级等相关数据,分析学情,设计教学目标和活动,创设网络与实操学习相结合的学习环境。教学中，运用智能化设备组织教学活动，如准备活动时运用心率手环监测学生热身状况;动作练习过程中，手机录制学生技术动作，采用"教练智眼"、NOKOV 动作捕捉系统等工具分析动作，获取精确数据反馈，据此调整学生的技术动作，帮助掌握更科学合理的技术动作;运用数字技术资源对学生进行德育教育，运用智能手环帮助学生通过可视化的数据体验坚持的积极影响，增强意志力。采用 APP 组织"定向越野"或"线上马拉松"等活动，以班级或寝室为单位，将成绩计入德育学分，提高团队协作和解决问题的能力。教学后，利用云端储存等系统，将学生每节课的运动表现，进行可视化的数据收集、分类、整理，形成运动记录档案，以便期末对学生学业成绩进行客观性的评价与打分。

引用格式 张艳,秦露祥,安晓红.新疆高校体育教师数字化教学能力的困境与纾困之道[C]//中国班迪协会（CBF）,广东省体能协会（GSCA）.2025 年第三届中国智慧体育科学大会论文集（下）.伊犁师范大学体育与健康学院;,2025:64-69.DOI:10.26914/c.cnkihy.2025.067303.

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行走过程中下肢外骨骼与人体交互力估算及应用

关键词

人机耦合系统；交互力；OpenSim；双层优化；MOPSO

摘要

在人机耦合系统中，交互力估算非常重要，是实现人机交互控制的基础，不仅对可穿戴机器人设备的结构设计与优化具有重大指导意义，而且对人机交互机理的理解具有极大促进作用。然而，受限于当前不成熟的力感技术、交互的复杂性和多样性，导致直接测量交互力存在极大挑战。在仿真环境下，提出交互力估算方法能为交互力的实际测量提供重要理论与技术支撑。

为此，本文借助 OpenSim 仿真平台，重点围绕步态过程中人与外骨骼交互力估算进行研究。首先，利用双层优化手段对人体模型标记点位置进行优化，得到与人体真实运动学模型匹配度高的人体虚拟模型。接着，基于优化后的虚拟模型关节角度信息，建立了满足胡克定律的交互力估算模型。然后，基于 SolidWorks 构建类人的外骨骼机器人，并利用前向动力学驱动外骨骼模型，结合提出的交互力估算模型，估算步态过程中人与外骨骼之间的交互力。最后，基于提出的交互力估算方法对步态过程中外骨骼绑带位置的优化问题进行建模，并分别从单目标和多目标层面对建立的优化问题进行求解。具体研究工作如下：

（1）提出了基于逆运动学(InverseKinematics,IK)的标记点双层优化算法。为提高人体虚拟模型与真实模型间的匹配度，基于模式搜索算法(PatternSearchAlgorithm,PSA)和 OpenSim 中的 IK 求解工具，提出一种双层优化方法对虚拟模型标记点位置进行优化。通过 6 个受试者的数值仿真，验证了所提双层优化方法的有效性。

（2）提出了一种估算人机耦合系统交互力的方法。首先，结合双层优化后的人体虚拟模型关节运动学特性，建立估算人机耦合系统交互力的模型。然后，将在 SolidWorks 中创建的外骨骼模型耦合到 OpenSim 中，并对其进行前向动力学仿真，确定交互力模型中弹簧弹性系数，用以对外骨骼髋、膝关节交互力进行估算。最后，通过数值仿真验证提出的交互力估算方法的有效性。

（3）提出了基于交互力估算模型的外骨骼绑带位置优化方法。首先，基于提出的交互力估算模型，建立外骨骼绑带位置优化问题数学模型。然后，分别从单目标和多目标优化两方面对建立的优化问题进行求解。在单目标求解时，利用曲线拟合方式，得到优化目标函数中权重系数比值与外骨骼绑带位置的解析表达式。在多目标优化过程中，提出一种多目标粒子群优化(Multi-Object Particle Swarm Optimization, MOPSO)算法对建立的优化问题进行求解，得到满足优化需求的 Pareto 非劣解集。最后，通过数值仿真验证了所提方法的有效性，并对单目标优化求解和多目标优化求解方法的优劣进行分析与说明。

本文研究结果表明：基于 IK 的标记点双层优化算法可显著降低模型误差，提高模型动态精度；利用提出的交互力估算方法对外骨骼关节交互力估算时，外骨骼关节处的交互力变化趋势与人

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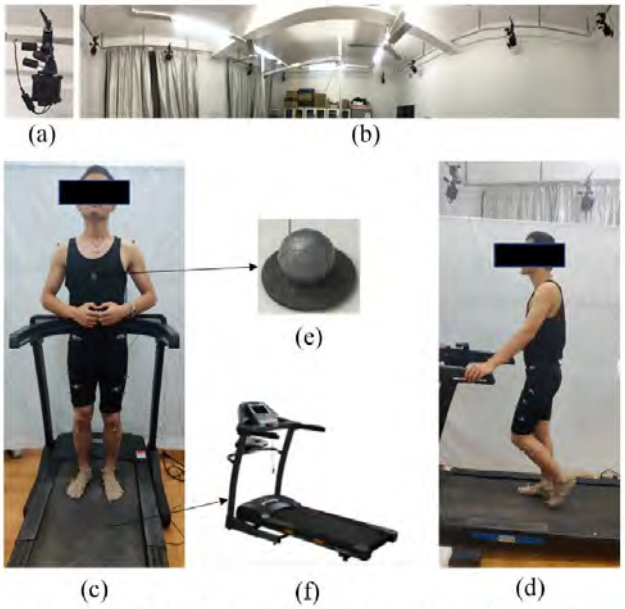
体关节真实运动信息变换趋势大体相同；基于交互力的外骨骼绑带位置优化能够根据决策者偏好设计出最优的绑带位置。因此，本文开展的人机耦合系统交互力估算仿真研究，不仅有望为人机耦合系统中交互力估算奠定理论基础，也能为步态行走过程中外骨骼机械结构设计与优化提供一定的技术支撑。



(a)红外摄像头 (b)动态捕捉系统全景 (c)实验者站立姿态
(d)实验者步态 (e)标记点 (f)跑步机
图 3-3 步态实验装置

NOKOV 度量动作捕捉在研究中的应用摘录

本文采用被动式光学运动捕捉系统(Nokov，北京度量科技有限公司)记录人体步态运动学信息。该系统共含 8 个高清摄像机，工作频率为 50Hz。红外摄像头通过捕捉标记点的运动，能精准捕捉目标在空间中的坐标信息。此外，运动捕捉系统配备上位机软件 Seeker，在界面上执行连杆模型显示、系统校准和数据保存与处理等操作。另外，Seeker 还可计算标记点之间的距离、角度、加速度等信息，并生成一个包含运动过程中每个标记点的坐标信息的 TRC 文件，用以在 OpenSim 中进行缩放(Scale)、逆运动学(IK)等操作。

引用格式 罗子涵.行走过程中下肢外骨骼与人体交互力估算及应用[D].武汉理工大学，2022.DOI：10.27381/d.cnki.gwlgu.2022.000182.

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https://kns.cnki.net/kcms2/article/abstract?v=DFdco8SIy0LHfGpBqZ6SaAv19c1ZhSI94WTIiJOt-gwaRmcBuBKDy8FkvMvVi1E15hfJu42fkx5miMzy3eKEJ6-hR1_ir9dxgIpU5i5dLuQOOPprflHS1w==&uniplatform=NZKPT&language=gb

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直立抗扰任务下踝关节外骨骼阻抗控制策略研究

关键词

踝关节外骨骼；直立抗扰；阻抗控制；人在回路；贝叶斯优化

摘要

外骨骼能够有效提高人体运动能力,比如:辅助患者运动康复、帮助老年人行走、帮助士兵负重行军等。运动过程中,外界干扰不可避免,外骨骼和人体如何共同应对外界扰动,保持身体平衡,是非常重要的研究课题。人体神经-肌肉-骨骼系统非常复杂,很难建立其精确的动力学模型。外界干扰具有偶发性质,与行走、奔跑类周期性动作不同,很难定义一个通用的模版。因此,在人机协作过程中,外骨骼控制缺乏对协作对象(人体)和协作任务(抗扰)的准确认知,很难制定出有效的控制策略。为此,本文首先简化外骨骼和抗扰任务,瞄准直立抗扰任务下踝关节外骨骼的控制问题,通过"人在回路"优化框架,获得外骨骼最优控制参数。具体研究工作如下:(1)建立人体踝关节力矩模型并设计了踝关节外骨骼机械结构。通过对直立抗扰过程中人体踝关节受力分析,基于倒立摆模型,建立踝关节力矩模型。在"沙袋撞击"实验中收集人体踝关节角度与力矩测量数据,以此为依据,完成踝关节外骨骼机械结构设计,通过 Bowden 绳连接外骨骼驱动装置与执行机构,降低外骨骼对穿戴者的负担。(2)提出了一种踝关节外骨骼分段阻抗控制策略。首先,通过直立抗扰实验,分析人体踝关节运动特性；然后,仿人体踝关节直立抗扰策略,制定分段阻抗控制策略,以期获得更好的"人机交互"控制效果。在分段控制的基础上,搭建外骨骼阻抗控制系统,并测试分析了控制器内环的力矩跟随效果。(3)设计了一种基于贝叶斯优化的"人在回路"外骨骼控制参数优化框架。在所设计的框架中,基于穿戴者比目鱼肌和胫骨前肌的肌肉激活程度,建立优化目标函数,利用贝叶斯优化算法对外骨骼控制系统的阻抗参数进行寻优。然后搭建直立抗扰实验平台,对所提方法进行对比实验验证。实验结果表明:基于分段阻抗控制策略的踝关节外骨骼能够有效协助人体实现直立抗扰,并降低人体下肢肌肉激活程度和踝关节力矩；基于贝叶斯优化的"人在回路"优化框架,能够为穿戴者提供个性化的最优阻抗控制参数,并进一步降低穿戴者下肢肌肉激活程度和踝关节力矩,在直立抗扰任务中为穿戴者提供更加积极有效的辅助作用。本文开展的简单任务下单关节外骨骼人机协作控制研究,将为今后复杂任务下多关节外骨骼的人机协作研究奠定基础。

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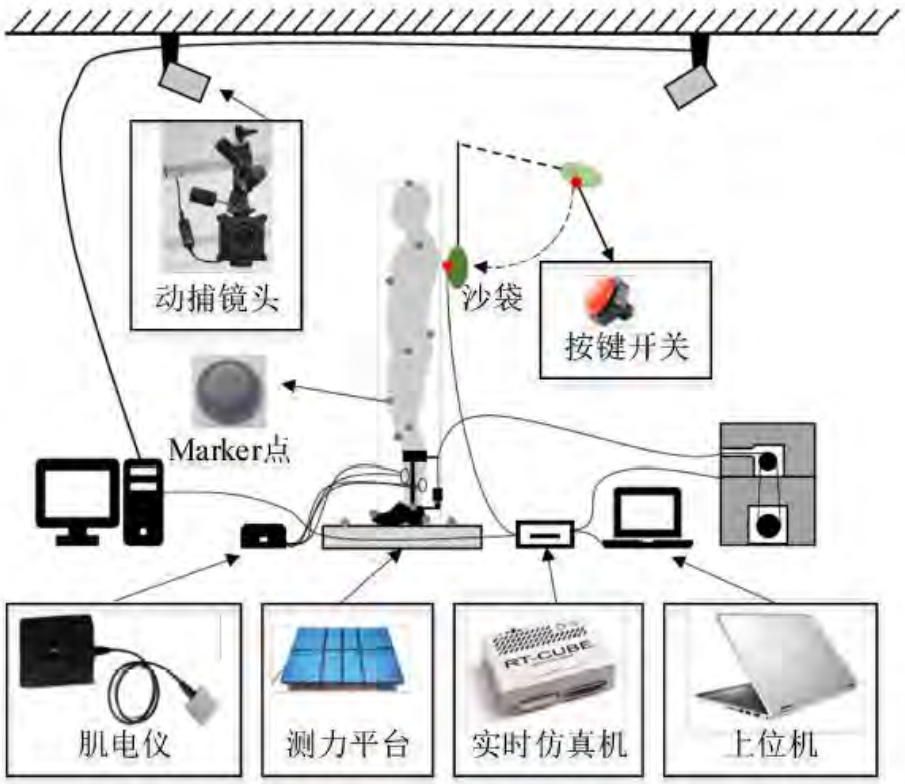

图 5-1 外骨骼辅助人体直立抗扰实验平台

NOKOV 度量动作捕捉在研究中的应用摘录

> *本文采用了"沙袋撞击"方案进行直立抗扰实验。在本章节设计的直立抗扰实验中，动作捕捉系统采用了 NOKOV 光学三维动作捕捉系统。该系统采用了被动式红外光原理设计，包含 8 组摄像头，可以记录每个光标点（也被称为 Marker 点）的运动信息（包括位置，速度和加速度）。在具体实验过程中，本文使用了 23 个 Marker 点标记受试者的位置信息。其中受试者身体上 19 个标记点，站立平面 4 个标记点。*

引用格式 严鹤.直立抗扰任务下踝关节外骨骼阻抗控制策略研究[D].武汉理工大学，2021.DOI：10.27381/d.cnki.gwlgu.2021.000401.

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准被动式变刚度踝关节助力外骨骼设计分析

关键词

准被动式；变刚度；踝关节助力；外骨骼设计；降低疲劳

摘要

为了降低人体踝关节跖屈时产生的力矩和减缓小腿肌肉疲劳为目的，设计了一款准被动式变刚度踝关节助力外骨骼， 利用足底压力信号控制电磁离合器工作的方式，实现储能单元的能量存储与释放。首先，变刚度机构是通过几何结构来调整 助力弹簧的预紧力，使关节输出刚度达到非线性特征，从而减少人体行走时的能量能耗。其次，建立了人体穿戴踝关节外骨 骼仿真模型，进行动力学仿真模拟，验证了外骨骼机械结构的合理性及良好的助力效果。最后，搭建了踝关节助力外骨骼功 能测试实验平台，对变刚度储能机构进行了性能测试，结果显示穿戴外骨骼助力后胫骨前肌和腓肠肌的肌电信号平均降低了 12.29%和 39.26%，说明了穿戴外骨骼有效降低了肌肉疲劳，为可穿戴外骨骼的设计提供新的方法。

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图 31　步态实验场景

NOKOV 度量动作捕捉在研究中的应用摘录

本文采用 NOKOV 三维运动采集分析系统获取人体下肢运动步态数据。
为了全面验证本文设计的踝关节外骨骼助力性能有效性，采用 NOKOV 三维运动捕捉系统进行步态实验，如图 31 所示。

引用格式 唐欣尧,杨佳音,王旭鹏,等.准被动式变刚度踝关节助力外骨骼设计分析[J/OL].机械工程学报,1-13[2025-09-16].https://link.cnki.net/urlid/11.2187.TH.20250217.1510.005.

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VIII. Inspection Robot

A Hybrid-Dimensional Laser SLAM Framework for Indoor Quadruped Inspection Robots

Keywords

Graph-based simultaneous localization and mapping (SLAM), indoor localization, laser inertial odometry (LIO), mobile robots, quadrupedal robots

Abstract

Based on their balance of movement flexibility, obstacle-surmounting ability, and load capacity, quadruped robots are increasingly employed in industrial inspections. Quadruped robots usually utilize laser simultaneous localization and mapping (SLAM) for autonomous navigation. However, SLAM coupled with legged odometry is susceptible to inaccuracies under the rapid movement and rotation of quadruped robots. To address this challenge, this article proposes a hybrid-dimensional laser SLAM framework for indoor quadruped robots that operates using only 3-D hybrid solid-state LiDAR and inertial measurement unit (IMU), eliminating the need to improve legged odometry accuracy, and adapts to any model of quadruped robot. The framework facilitates high-bandwidth and high-frequency dead-reckoning using laser inertial odometry (LIO) based on point-to-map matching. This prior for scan matching, along with motion blur removed, multiframe fused, and 2-D compressed LiDAR scans, are input into graph-based SLAM to obtain optimized pose estimations and 2-D grid maps. Optimized poses further enhance the accuracy of 3-D point cloud maps generated by LIO. The effectiveness of the framework is demonstrated through experiments conducted with the quadruped robot in simulated train depot inspection scenarios. Compared to graph-based SLAM without and with legged odometry as scan matching prior, the proposed framework exhibits enhanced mapping accuracy and repeated localization precision.

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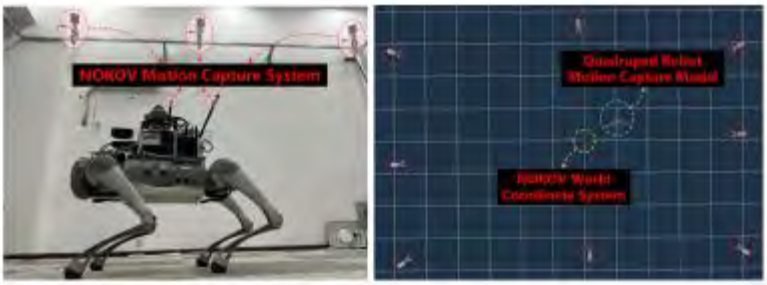

Fig. 15. Quadruped robot and NOKOV motion capture system.

How NOKOV Contributes to the Research

To evaluate the enhancement in trajectory estimation accu-racy of the proposed framework compared to baselines, the NOKOV motion capture system is utilized to obtain the groundtruth of the robot's trajectory.Fig.15demonstrates how thesystem tracks the robot's pose in real time within the motioncapture environment. The NOKOV system operates with atracking frequency of 240 Hz and a tracking precision of ±0.002 m.

Citation Cheng J, Zhang M, Ma L, et al. A hybrid-dimensional laser slam framework for indoor quadruped inspection robots[J]. IEEE Sensors Journal, 2024, 24(10): 16935-16942.

Link https://ieeexplore.ieee.org/abstract/document/10489846

A Lie-Theory-Based Dynamics Modeling Method of Snake-Arm Robot With Virtual Linkage Criterion

Keywords

nake-arm robots, dynamics, cable-driven, hyperredundant, lie theory

Abstract

Cable-driven snake-arm robots with high degrees of freedom and flexible, slender bodies are very suitable for applications in unstructured, narrow situations. For the high-performance development of snake-arm robots, dynamics modeling is a very important issue but very difficult due to the hyperredundant degrees of freedom and long transmission chains. Thus, a recursive dynamics modeling method based on the Lie theory is proposed for the cable-driven snake-arm robot. First, the motion mapping relationship among the driving cables, universal joints, and end-effector is established based on the product of an exponential formula, which is helpful to reduce the complexity of modeling. To solve the kinematic spinor coupling problem of two rotating axes of a universal joint, a virtual linkage law is proposed. Based on the virtual linkage law, Newton – Euler method, and Lie theory, the dynamics equation of a snake-arm robot is derived. The computational complexity of the established dynamics model is \\(O(n) \\). Furthermore, a dynamic feedforward proportional-derivative (PD) control framework based on kinematics and dynamics is constructed. Finally, experiments based on the developed 21-degree-of-freedom (DOF) snake-arm robot are conducted, whose results prove the validation of the proposed method. Compared with the pure PD control strategy, the proposed dynamic feedforward control strategy improves the repeatability of the snake-arm robot in the X, Y, and Z directions by about 70.3%, 69.3%, and 61.4%, respectively. The experimental results show that the dynamic model is helpful in improving the motion accuracy of the snake-arm robot.

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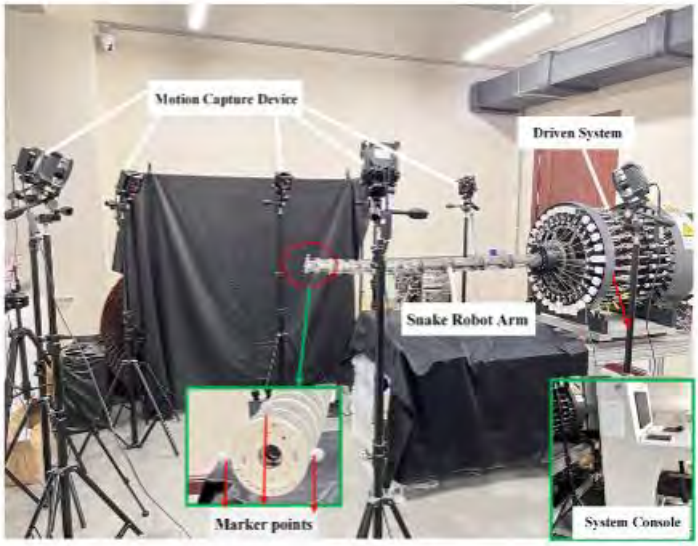

Fig. 6 The experimental system platform

How NOKOV Contributes to the Research

4 Experimental Verifcation and Discussions
4.1 The Hardware of the Experimental System. A cable-driven snake-arm robot has been developed to verify the dynamic and control studies conducted. The robot system consists of the snake-arm body, a drive system, and a sliding platform, with a total of 11 (10+1) joints and 21 (20+1) degrees of freedom. This includes 10 universal joints with two degrees of freedom each, as well as one moving joint with one degree of freedom. Each universal joint is driven by three cables, each connected to a by the Nokov Mars 2H for analysis of the performance of the presented method; its parameters are shown in Table 2. The prototype for the robot is shown in Fig. 6, and its parameters are provided in Table 3.

Citation Wang Y, Tuo G, Li T, et al. A Lie-Theory-Based Dynamics Modeling Method of Snake-Arm Robot With Virtual Linkage Criterion[J]. Journal of Mechanisms and Robotics, 2025, 17(11): 111011.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001590265300010

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A Novel Variable-Diameter-Stiffness Cable-Driven Serpentine Manipulator: Design, Modeling, and Characterization

Keywords

Cable-driven, design and modeling, experiments, serpentine manipulator, variable diameter-stiffness

Abstract

Cable-driven serpentine manipulators (CSMs), due to their unique flexibility of movement, have broad application prospects in unstructured and confined environments. To enhance adaptability to different environments and tasks, the design of variable stiffness structures has long been a research focus for CSMs. Inspired by spatial folding mechanisms, such as umbrellas, we propose a novel variable-diameter-stiffness cable-driven serpentine manipulator (VDS-CSM). The standout feature of this innovation is its ability to achieve integrated control over both the outer diameter and the stiffness of the manipulator. First, we present the structural design of the novel VDS-CSM, whose outer diameter and stiffness can be continuously adjusted. Second, we establish the kinematics, statics, and stiffness models for VDS-CSM. Based on this, we conduct an in-depth study of the manipulator's stiffness characteristics. Simulation data indicate that the change ratio of the manipulator's end stiffness is approximately proportional to the square of the change ratio in the manipulator's outer diameter. Finally, we build a VDS-CSM experimental system. Through experiments, the accuracy of the proposed model for VDS-CSM is verified. The experimental results show that the outer diameter and stiffness of the manipulator can vary by 200% and 400%, respectively.

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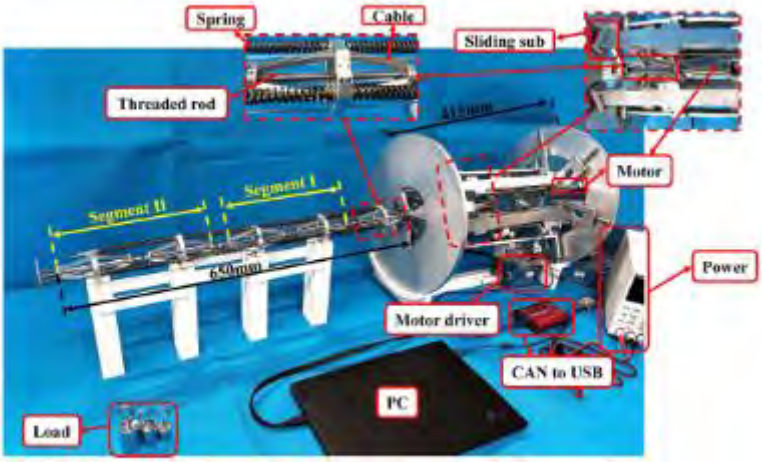

Fig. 16. Prototype and experimental system of VDS-CSM.

How NOKOV Contributes to the Research

In the experiment, the NOKOV optical motion capture systemwas used to measure the displacement change at the end ofVDS-CSM after external force was applied at different radiusstates. Based on the measurement data, the theoretical stiffness,measured stiffness, and error at the end of VDS-CSM are pre-sented in Fig.19. These experiments validate the accuracy ofthe stiffness model for VDS-CSM and demonstrate its effectiveouter diameter-stiffness integration adjustment capability.

Citation Meng D, Guo T, Ma Z, et al. A Novel Variable-Diameter-Stiffness Cable-Driven Serpentine Manipulator: Design, Modeling, and Characterization[J]. IEEE/ASME Transactions on Mechatronics, 2025.

Link https://ieeexplore.ieee.org/document/11018755

A toe-inspired rigid-flexible coupling wheel design method for improving the terrain adaptability of a sewer robot

Keywords

sewer robot, toe joint, rigid-flexible structure, flexible joint, rigid-flexible coupled dynamics

Abstract

The human toe, characterized by its rigid-flexible structure comprising hard bones and flexible joints, facilitates adaptive and stable movement across varied terrains. In this paper, we utilized a motion capture system to study the adaptive adjustments of toe joints when encountering obstacles. Inspired by the mechanics of toe joints, we proposed a novel design method for a rigid-flexible coupled wheel. The wheel comprises multiple elements: a rigid skeleton, supporting toes, connecting shafts, torsion springs, soft tendons, and damping pads. The torsion springs connect the rigid frame to the supporting toes, enabling them to adapt to uneven terrains and pipes with different diameters. The design was validated through kinematic and dynamic modeling, rigid-flexible coupled dynamics simulation, and stress analysis. Different stiffness coefficients of torsion springs were compared for optimal wheel design. Then, the wheel was applied to a sewer robot, and its performance was evaluated and compared with a pneumatic rubber tire in various experiments, including movement on flat surfaces, overcoming small obstacles, adaptability tests in different terrains, and active driving force tests in dry and wet pipelines. The results prove that the designed wheel showed better stability and anti-slip properties than conventional tires, making it suitable for diverse applications such as pipeline robots, desert vehicles, and lunar rovers.

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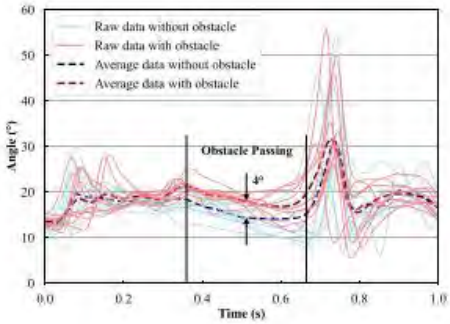
(a)



(b)

Figure 2. Experiments on the toe joints using a motion capture system. (a) An example of the marker placements on the right foot of a subject, with the ankle, toe and toe joint markers. (b) Comparison of toe joint angles across two gait cycles in normalized time.

How NOKOV Contributes to the Research

In the experiments, a NOKOV motion capture system was used to record foot movements. The system comprised six cameras capable of capturing the positions of reflective markers attached to the foot, It offered a capture frame rate of up to380 Hz, an image resolution of 2048 x 1088, and amaximum observation distance of 2l m.

Citation Zhang J, Chen X, Shen W, et al. A toe-inspired rigid-flexible coupling wheel design method for improving the terrain adaptability of a sewer robot[J]. Bioinspiration & Biomimetics, 2024, 19(4): 046003.

Link https://iopscience.iop.org/article/10.1088/1748-3190/ad41af

Achieving Cross-domain NLOS Localization via Edge-assisted Semi-supervised Learning

Keywords

Edge-assisted, semi-supervised, NLOS mitigation, ultra-wideband localization

Abstract

The localization of coal mine robots (CMRs) serves as the foundation for intelligent mines. Despite various approaches proposed by academia and industry, existing range-based localization methods generally encounter the non-line-of-sight (NLOS) problem, leading to severe accuracy degradation in complicated underground mines. Facing the above challenge, this paper proposes an edge-assisted cross-domain NLOS localization (CrossDNL) framework based on semi-supervised learning. Specifically, we analyze the channel impulse responses (CIRs) of ultra-wideband (UWB) to identify the multi-channel NLOS conditions and further mitigate ranging errors via the deep neural network (DNN). To achieve reliable localization across various scenarios, CrossDNL adopts an edge-assisted semi-supervised learning architecture that enables it to optimize DNN models by self-training on the edge server and achieve the real-time service on the CMR. Besides, we propose a range-based error state Kalman filter (ESKF) scheme to improve the localization performance. We implement CrossDNL on the CMR and the edge server and evaluate it in various scenarios. Results show that CrossDNL can achieve a 14cm localization error in real time, outperforming the latest solutions by more than 15%.

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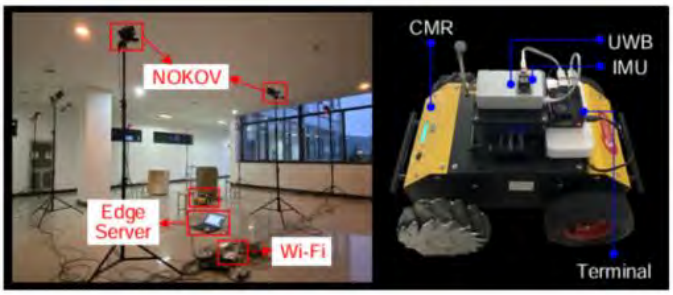

Fig. 14. The indoor corridor environment and the CMR platform.

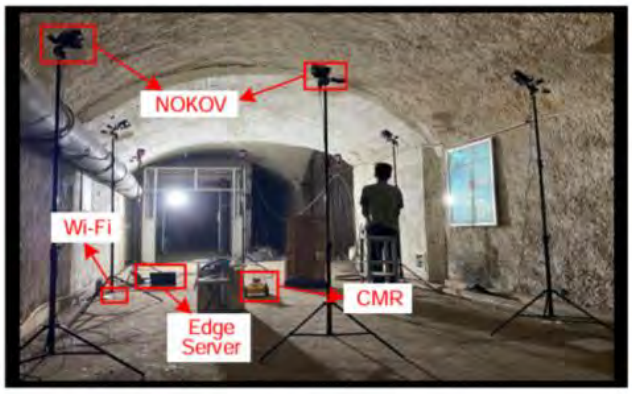

Fig. 19. The coal mine experimental environment.

How NOKOV Contributes to the Research

The experiments are based on the UWB P440 module produced by Time Domain Company for CIRs acquisition. TW-TOF protocol is adopted for ranging, which can provide the accuracy of several centimeters with LOS conditions. The discrete waveform related to each UWB range measurement is obtained based on the CIRs. For the received CIRs, we record the sample amplitudes with the 61ps Nyquist sampling rate in a 21ns window. Besides, we utilize the optical 3D motion capture system (NOKOV) to achieve the location of anchors, the range between the anchor and CMR, and the pose of CMR, which can provide sub-millimeter localization accuracy.

Citation Chen P, Zhang K, Gao S, et al. Achieving Cross-domain NLOS Localization via Edge-assisted Semi-supervised Learning[J]. IEEE Transactions on Wireless Communications, 2025.

Link https://ieeexplore.ieee.org/document/10974458

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Bio-Inspired Locomotion Control of Gecko-Mimic Robot: From Biological Observation to Robot Control

Keywords

Symbiosis, Animals, Dynamics, Prototypes, Robot sensing systems, Solids, Mathematical models

Abstract

By studying animal and human locomotion strategies, mechanisms, patterns, kinematics, and dynamics, bio-inspired locomotion aims to establish a new theory and method of bionic mechanism, motion planning, and stable control, as well as a new concept for developing bio-inspired robots and unmanned systems. Throughout the long history of evolution, animals have shaped robust, complex, and adaptive movements in order to live in difficult environments. Nature provides an endless supply of robot design concepts for many environmental conditions, such as flight [1], swimming [2], and terrestrial movement [3].

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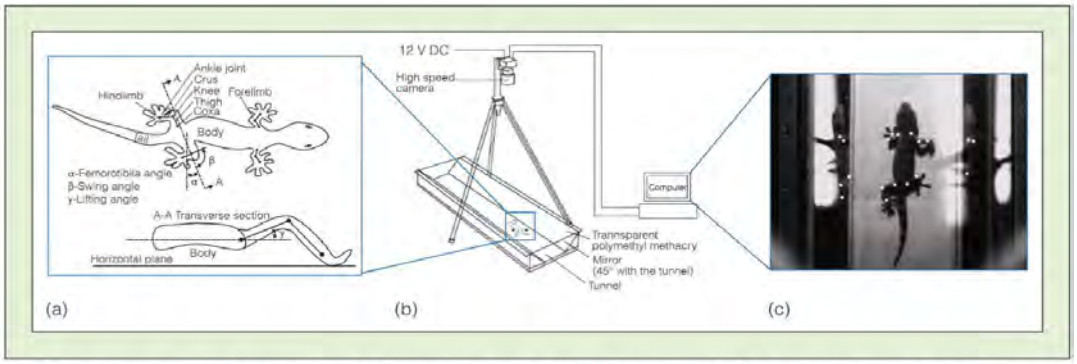

Fig. 2. The locomotion observation system for gecko. (a) The predefined angles; (b) Observation equipment; (c) Gecko photograph captured while moving. (Adapted from [16] with permission ©2009 Springer Nature.)

How NOKOV Contributes to the Research

For locomotion experiments, a variety of motion capture techniques and technologies have been created \[15]. Com-mercial motion capture equipment is easy to use and comes with user-friendly software like OptiTrack (Corvallis, Ore-gon, USA), Vicon (Oxford, England, UK), NOKOV (Beijing, China) and others. The positions of the markers are tracked and captured by optical cameras, and then the trajectories can be generated directly from the software by placing them on the predetermined places in preparation. However, a special setup is required because the markers are difficult to stick to a small animal's body. A high-speed camera can clarify what is otherwise fuzzy or too fast to see and has enabled significant resolution of movement.

Citation Li H, Zhu G, Arena P, et al. Bio-inspired locomotion control of gecko-mimic robot: From biological observation to robot control[J]. IEEE Instrumentation & Measurement Magazine, 2022, 25(9): 28-35.

Link https://ieeexplore.ieee.org/abstract/document/9955470

Cable Force Distribution and Motion Control for a Cable-Driven Super-Redundant Robot Under Stiffness Constraints

Keywords

cable-driven super-redundant robot, stiffness modeling, cable force distribution, motion control, bio-inspired

Abstract

Cable-driven super-redundant robots (CDSSR) with slender and flexible bodies have wide application potential in narrow spaces. However, the control accuracy of the robot is affected by the instability of the operating stiffness during motion, which is related to the diversity of the cable tension distribution solutions. To solve this problem, an analytical stiffness model of the cable-driven super-redundant robot is first constructed based on the virtual work principle. Then, an optimal cable tension distribution model based on energy optimization and stiffness constraint is proposed. Third, a motion control framework of cable-driven super-redundant robot with stiffness constraints is proposed. Finally, constant stiffness control experiments and repeated positioning accuracy experiments of robot end under different end stiffness conditions are carried out on a 21-DOF cable-driven super-redundant robot. The results show that the proposed control strategy can achieve constant stiffness control. When the stiffness of the robot is adjusted from 200 N/m to 300 N/m, the repeated positioning accuracy in the X, Y, and Z directions is increased by 40.00%, 27.62%, and 53.09%, respectively. When the end stiffness is adjusted from 300 N/m to 400 N/m, the repeated positioning accuracy in the X, Y, and Z directions is increased by 40.81%, 58.08%, and 64.99%, respectively. The experimental results show that the proposed cable force distribution model and control strategy are effective.

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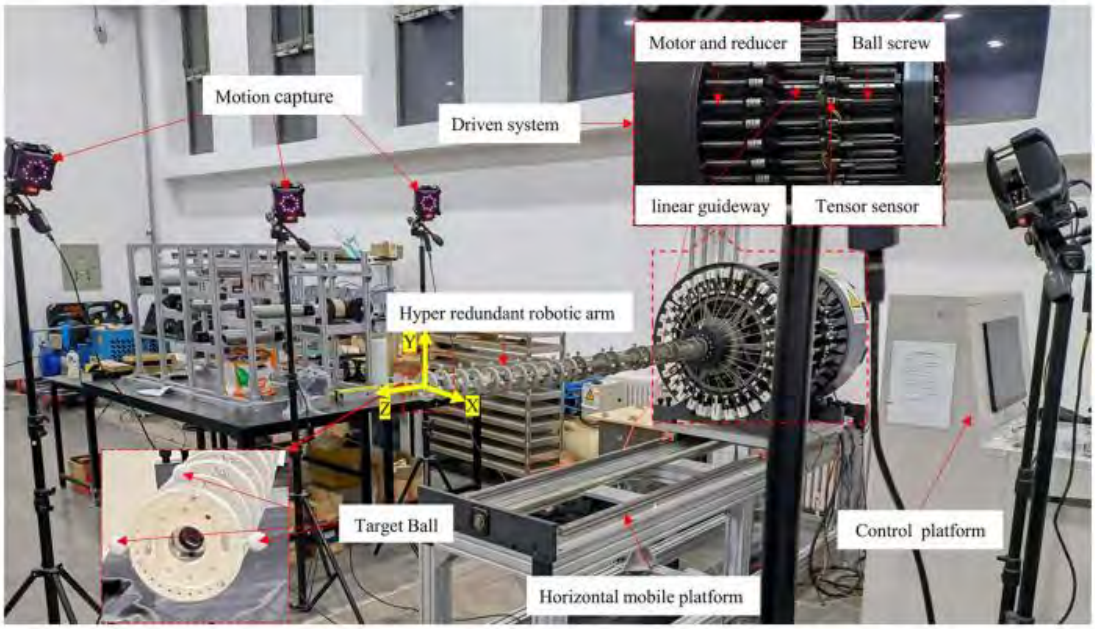

Fig. 8 The experimental system platform

How NOKOV Contributes to the Research

Each of the universal joints is driven by three cables. Each cable is powered by a set of modular driving mechanisms to provide linear motion. Detailed parameters are shown inTable1. The Nokov Mars 9Hmeasuring system was used to record the motion data of the CDSSR, and the control effect of the proposed method was analyzed. The parameters of the measuring system are shown in Table2.

Citation Tuo G, Wang Y, Li T, et al. Cable Force Distribution and Motion Control for a Cable-Driven Super-Redundant Robot Under Stiffness Constraints[J]. Journal of Mechanisms and Robotics, 2025, 17(6): 061012.

Link

https://asmedigitalcollection.asme.org/mechanismsrobotics/article/17/6/061012/1210230/Cable-Force-Distribution-and-Motion-Control-for-a?searchresult=1

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Climb-Odom: A robust and low-drift RGB-D inertial odometry with surface continuity constraints for climbing robots on freeform surface

Keywords

Climbing robot, Visual-inertial odometry, Sensor fusion, Autonomous localization, 3-D reconstruction

Abstract

Low-drift localization and reliable yaw orientation estimation remain challenging for visual-inertial odometry (VIO) without loop closure, especially for climbing robots in weak-featured environments. In this article, we proposed a robust and low-drift RGB-D inertial odometry named Climb-Odom for climbing robots on large freeform surfaces. The odometry consists of a real-time 6-DOF (degree of freedom) pose estimator and an optimized point cloud map. The estimator incorporates surface continuity constraints in addition to visual and inertial constraints to realize low-drift localization. The point cloud map is reconstructed rectifying translation errors in surface normal and rotation errors around gravity by map optimization and merging. On the low-textured and freeform challenging surface, Climb-Odom still shows robust and accurate localization performance and effectively reconstructs the traveled area with high quality. Experiments with the climbing robot on a real wind turbine blade demonstrate that Climb-Odom outperforms state-of-the-art RGB-D inertial odometry and SLAM systems. For the zig-zag trajectories covered by the climbing robot, the localization root mean square error (RMSE) of Climb-Odom are less than 0.42% in all datasets while aligned by the origins. The RMSE of iterative closest point (ICP) result between the largest reconstructed map and the reference point cloud is less than 7 mm within approximately 5.6 m2.

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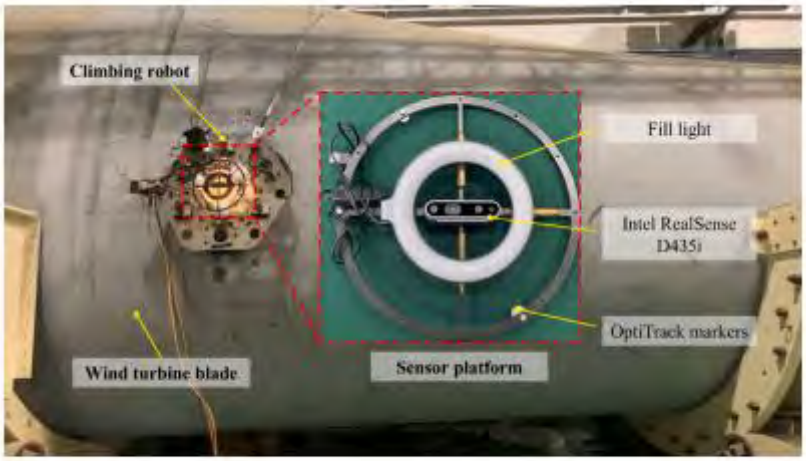

Fig. 5. The climbing robot and sensor platform. The sensor platform consists of a fill light and an Intel RealSense D435i. D435i is an RGB-D camera with a built-in IMU.

How NOKOV Contributes to the Research

There was a fill light settled on the bracket to ensure the illumination consistency assumption of the optical flow algorithm. The attached work piece is a portion of a real large wind turbine blade (6.0x2.4x 3.6 m),whose curvature varies between 0.2 m-1 and 1 m-1. For the collection of reference ground truth, we used a professional optical motion tracking system NOKOV, which consists of four Mars2H cameras on a side of the wind turbine blade.

Citation Gu Z, Gong Z, Tan K, et al. Climb-Odom: A robust and low-drift RGB-D inertial odometry with surface continuity constraints for climbing robots on freeform surface[J]. Information Fusion, 2025, 117: 102880.

Link https://dl.acm.org/doi/10.1016/j.inffus.2024.102880

Coverage path planning of bridge inspection with Unmanned aerial vehicle

Keywords

Unmanned aerial vehicle, Coverage path planning, Particle swarm optimization, Bridge inspectio

Abstract

To address the low efficiency of bridge inspection using Unmanned Aerial Vehicle (UAV) due to redundant inspection viewpoints and frequent sharp maneuvers, this paper proposes a novel coverage path planning model that leverages artificial intelligence methods. Firstly, to minimize viewpoint redundancy, a Collaborative Greedy Neighborhood (CGN) algorithm is introduced to optimize the distribution of viewpoints. This method preprocesses the bridge model using Voronoi diagrams and generates optimal viewpoints by fully considering constraints such as camera field of view and gimbal angles. Secondly, in solving the UAV path planning problem, factors including collision risks between the UAV and the bridge, path length, frequency of steep ascents, and sharp turns are comprehensively considered. An improved Particle Swarm Optimization (PSO) algorithm based on a Greedy Strategy (Greedy Strategy-Improved PSO, GS-IPSO) is proposed to achieve global optimization of the path. The simulation results show that compared with the viewpoint offset method, Q-learning algorithm and clustering algorithm, the proposed CGN algorithm has significant advantages in significantly reducing the number of required viewpoints. In addition, in the path planning task, the GS-IPSO algorithm can not only effectively shorten the path length, but also significantly reduce the number of sharp turns and rapid climbs and descents compared to the traditional PSO algorithm and enhanced discrete particle swarm optimization (Enhanced-DPSO) algorithm, thereby significantly improving the inspection efficiency and reliability. Finally, through experimental verification in a real-world environment, the practicality and effectiveness of the method proposed in this paper are further confirmed.

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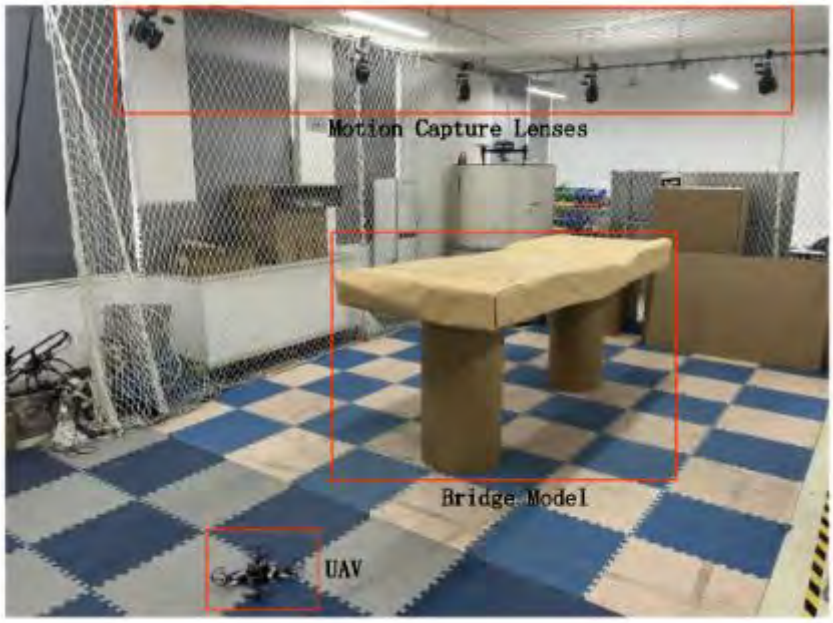

Fig. 7. Experimental environment.

How NOKOV Contributes to the Research

In this experiment, the NOKOVoptical3D motion capture system was used to capture the UAV's position information and movement trajectory data. The UAV viewpoints generated in the simulation were imported into the system, and a start command was issued. The UAV took off from the starting point and performed an inspection flight around the bridge. Upon reaching each viewpoint, the UAV made a brief stop before continuing its flight until it reached the last viewpoint and completed the flight. After the UAV bridge inspection path experiment was completed, the flight data obtained in the experimental environment was imported into the simulation system for comparison and analysis with the simulation results.

Citation Li X, Chen Y, Chen Z, et al. Coverage path planning of bridge inspection with Unmanned aerial vehicle[J]. Engineering Applications of Artificial Intelligence, 2025, 156: 111253.

Link https://www.sciencedirect.com/science/article/abs/pii/S0952197625012540

Design and Analysis of Hybrid Robots for Powerline Inspection

Abstract

Hybrid robots, which combine crawling and flying capabilities, have gained significant attention in recent years due to their potential in powerline inspection. This paper provides insights into the design of hybrid robots, offering a comprehensive analysis of the system's design requirements and its solutions. Firstly, we present a detailed overview of the hybrid robot's system architecture, encompassing the design aspects of its mechanical, hardware, and software components. Secondly, we analyze the dynamics of the robot in crawling mode, deducing the conditions necessary for maintaining balance on powerlines and traversing inclined powerlines. Thirdly, we investigated the kinematics and dynamics of the robot in flight mode, examining how the structural design of the hybrid robot specifically impacts its system dynamics and control responsiveness. Finally, we verify our analyses through a series of simulations and real-world tests, confirming the effectiveness and feasibility of the design strategies presented.

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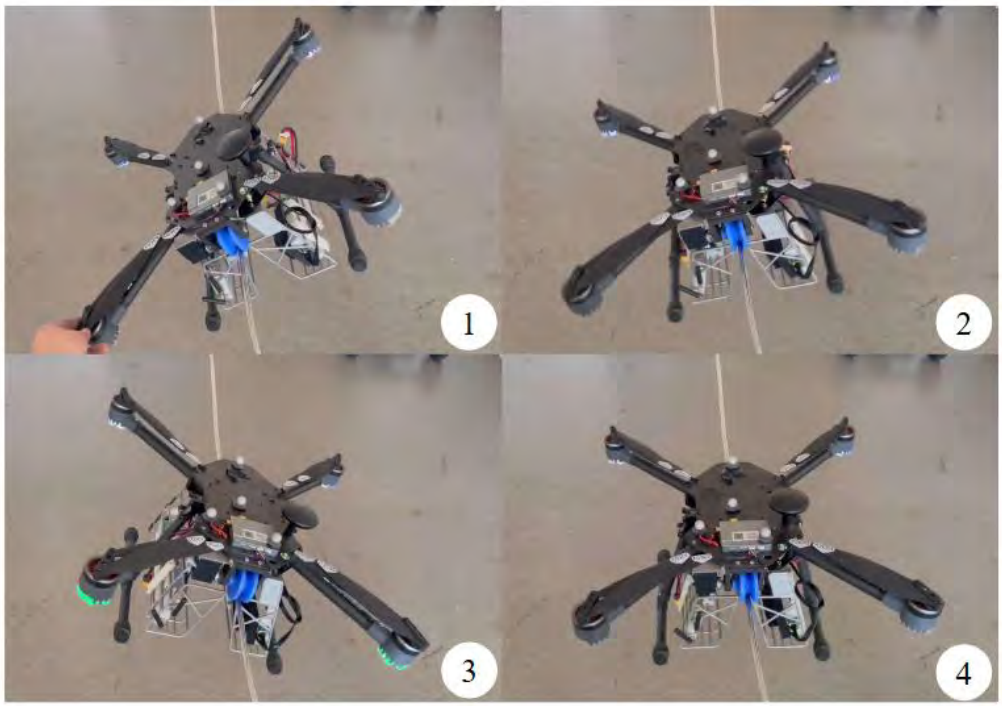

Fig. 8. Balance test of the hybrid robot on powerline. The numbers denote the evolution of the hybrid robot returning to the balance state.

How NOKOV Contributes to the Research

Fig. 9 presents the roll angle of the robot recorded by the NOKOV Motion Capture System.

Citation Z. Li, Y. Tian, G. Yang, Y. Zhang, E. Li and Z. Liang, "Design and Analysis of Hybrid Robots for Powerline Inspection," 2024 IEEE 20th International Conference on Automation Science and Engineering (CASE), Bari, Italy, 2024, pp. 3654-3659, doi: 10.110

Link https://ieeexplore.ieee.org/document/10711700

Design and Control of a Fully Actuated Aerial Manipulator System for Measuring the Thickness of Metal Facilities

Keywords

Aerial contact inspection, aerial manipulator (AM), aerial physics interaction, force control, autonomous aerial vehicle (AAV)

Abstract

An aerial manipulator (AM) system for thickness measurement of metal facilities is introduced in this article, which includes a fully actuated flying platform and an end effector. The AM utilizes the fully actuated advantage of the flying platform to apply controlled contact forces to the environment without the need for complex robotic manipulators. An end effector is designed, which includes an ultrasonic thickness (UT) probe mounted on a spring-damping buffer, and a coupling agent injection device allows the coupling to be applied during the inspection process. We divide the aerial inspection process into two phases: the approach phase and the contact phase. In the approach phase, we design a yaw control assistance method to ensure that the AM can contact the target surface with the desired yaw, even outside the operator's line of sight. In the contact phase, a parallel force/velocity controller tailored to the motion characteristic of the AM is proposed to achieve precise contact force control. A switching function is designed to ensure stable transitions between the motion control and force control. The control effectiveness and the ability to measure the thickness of the metal facility of the AM system are demonstrated by practical experiments.

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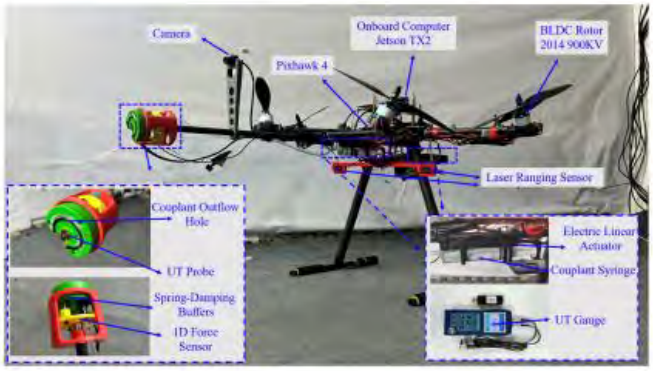

Fig. 2. Overview of the proposed AM system components.

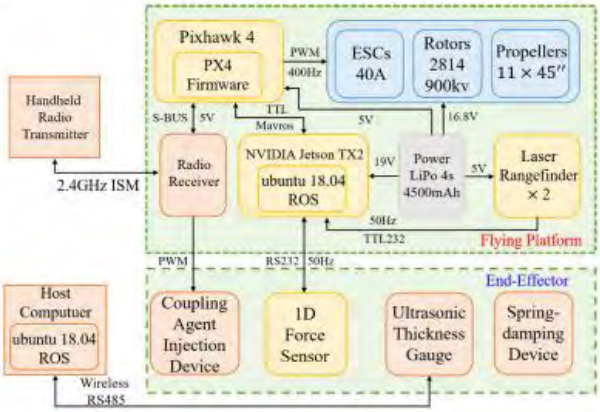

Fig. 3. Software and hardware frameworks of AM.

How NOKOV Contributes to the Research

The designed AM system, along with its hardware and software framework, is illustrated in Figs. 2 and 3. The NOKOV motion capture system provides the position and yaw data for the AM, while other attitude information is obtained from the Pixhawk 4's built-in IMU. The activation of the yaw control assistance and the parallel force/velocity controller is managed via different channels on the handheld radio transmitter.

Citation Hao S, Mao J, Zhang J, et al. Design and Control of a Fully Actuated Aerial Manipulator System for Measuring the Thickness of Metal Facilities[J]. IEEE Transactions on Instrumentation and Measurement, 2025.

Link https://www.x-mol.com/paper/1894909161115312128

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Design and Development of an Inchworm-Like Robot with Its Generalized Climbing Path Planning

Keywords

nchworm-like robot, Multi-objective design, Climbing gait planning

Abstract

This paper presents a novel 6-degree-of-freedom (DOF) inchworm-like robot inspired by bionics, designed to perform pipe inspection tasks with high flexibility in complex, unstructured environments. To determine the optimal dimensions of each link, a Nash bargaining solution-based multi-objective optimization framework is developed, evaluating performance indicators such as reachable workspace, global manipulability, and acceleration capability. Inspired by the inchworm locomotion, three distinct climbing gaits are designed to enhance adaptability in confined and irregular spaces. To ensure safe and reliable operation, transition analysis is conducted and the operational workspace is systematically calculated. Moreover, a novel global path planning algorithm specially designed for the inchworm-like robot, termed inchworm-like robot rapidly-exploring random tree (ICHRRT\), is proposed. As an improved algorithm of RRT\, this method integrates gait planning and transition analysis to generate feasible and collision-free paths tailored to the robot's unique structure and motion characteristics. A physical prototype is developed, and truss-crossing experiments are conducted in a truss environment. Experimental results validate the robot's superior climbing capability and its effectiveness in navigating obstacles.

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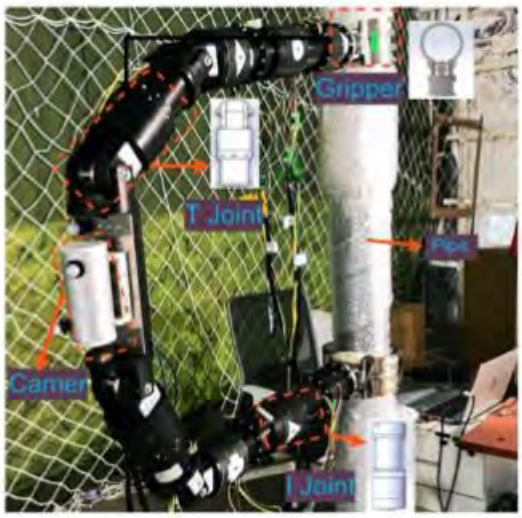

Figure 2 Prototype of the inchworm-like robot

How NOKOV Contributes to the Research

5.1 Experimental Setup
The experimental prototype is fabricated as illustrated in Figure 2. The shell material of the inchworm-like robot is aluminum, while the grippers are made of steel. The control system of the robot prototype is shown in Figure 12. A PC serves as the top controller. It can plan the path, manage the motion gait, and calculate the control torque of each joint. The PC is connected to the motor drivers via CANopen protocol. The motion drivers out-put control current to the motor to realize the control of the joint motors. The experiments are carried out in an indoor laboratory equipped with the NOKOV motion capture system, which includes 48 motion capture cam-eras (a tracking accuracy of 0.1 mm and a tracking range of 13 m×8 m×3 m, see Figure 13). Markers are attached to various parts of the inchworm-like robot to capture its movement during the test. The experimental setup consists mainly of two pipe trusses and the ground. Each truss is composed of three pipes with a diameter of 100 mm. The pipe trusses are made of steel (see Figure 13).

Citation Zhu M ,Du Y ,Chen X , et al.Design and Development of an Inchworm-Like Robot with Its Generalized Climbing Path Planning[J].Chinese Journal of Mechanical Engineering,2025,38(04):174-187.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001545426900001

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Design and omnidirectional motion control of a circular concrete bridge pier climbing robot

Keywords

Bridge pier inspection robot, Omnidirectional motion, Attitude estimation, LSTM-RF, DQN-Tube MPC

Abstract

Purpose– This study aims to address the challenges of the automated inspection of concrete bridge piers, as existing climbing robots often encounter constraints related to their adhesion methods. Furthermore, achieving consistent omnidirectional movement on these large vertical structures is a complex control task that evaluates traditional estimation and control techniques.

Design/methodology/approach – This study addresses these limitations by presenting an innovative climbing robot featuring a distinctive force-controlled gripping mechanism for robust, adaptable adhesion and Mecanum wheels for full omnidirectional movement. To achieve accurate control in complex scenarios, this paper presents two methodologies: a Long Short-Term Memory Random Forest (LSTM-RF) model that integrates data from multiple Inertial Measurement Units (IMU) for reliable attitude estimation, and a Deep Q-Network Tube Model Predictive Control (DQN-Tube MPC) framework for motion control.

Findings – The controller's remarkable tracking accuracy, with a Root Mean Square Error (RMSE) of 1.17 cm for the Zr-axis position, 1.17° for Roll, 0.78° for Pitch and 1.725° for Yaw angle.

Originality/value – The proposed robotic system offers an effective and dependable solution for the automated inspection of bridge piers.

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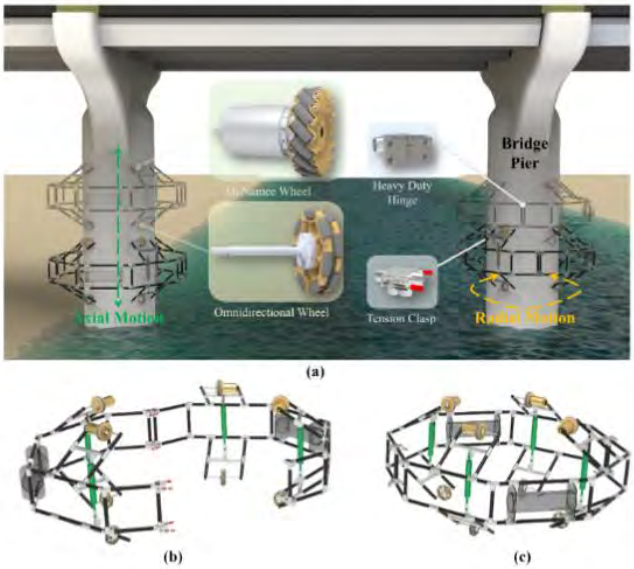
Figure 1 Conceptual illustration of the climbing robot for bridge pier inspection. (a) The robot is designed to operate in challenging environments, performing both axial and radial movements. (b) Its two-piece frame unfolds for rapid deployment onto the pier. (c) The robot is shown in its clamped state during inspection tasks



How NOKOV Contributes to the Research

The ground truth attitude data for training and validation was obtained using an 8-camera NOKOV Mars 26H motion capture system. This system is specified by the manufacturer to provide submillimeter accuracy for position tracking and an orientation accuracy of less than 0.1°, establishing a high-precision baseline for our evaluation. To capture the robot's motion, multiple reflective markers were strategically placed on the robot's main carbon fiber frame, defining a rigid body in the motion capture software. Before each set of trials, the system's global coordinate frame was calibrated and aligned with the pier's reference frame, ensuring that the Z-axis was oriented vertically along the pier. The data streams from the IMUs and the motion capture system were synchronized using a hardware trigger signal to ensure precise temporal alignment. The motion capture system recorded data at 120 Hz, which was subsequently processed offline. The processing involved downsampling the data to 50 Hz to match the IMU data frequency for a one-to-one comparison. Finally, a second-order low-pass Butterworth filter with a cutoff frequency of 5 Hz was applied to the resulting orientation data to remove any high-frequency noise or jitter from the marker tracking.

Citation Xie F, Mao J, Liu Y, et al. Design and omnidirectional motion control of a circular concrete bridge pier climbing robot[J]. Industrial Robot: the international journal of robotics research and application, 2025: 1-14.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001625786900001

Design of a Deployable Continuum Robot (DCR) With Coiling Mechanism

Keywords

Coiling mechanism, deployable continuum robot (DCR), variable kinematics motion control framework

Abstract

Continuum robots are highly suitable for interactive operations in confined spaces due to their inherent body compliance. However, traditional continuum robots with only bending degrees of freedom (DOFs) are limited in both workspace and dexterity, especially when manipulating an object near the proximal part of the arm. This article introduces a deployable continuum robot with a coiling mechanism, DCR, capable of fully stowing, or deploying, its arm into, or out of, a robot case with the help of a coiling mechanism. Deploying the continuum arm provides the robot with variable kinematics and workspace. A variable kinematics motion control framework is then established to enable the end-effector of the robot to smoothly travel through whole workspace while maintaining an optimal configuration. Based on this framework, visual servoing control methods can be applied to the robotic system, achieving high positioning precision up to 1 mm. Experimental results demonstrate that the proposed DCR enlarge the workspace and improve the manipulating dexterity, which are particularly beneficial to applications in confined spaces.

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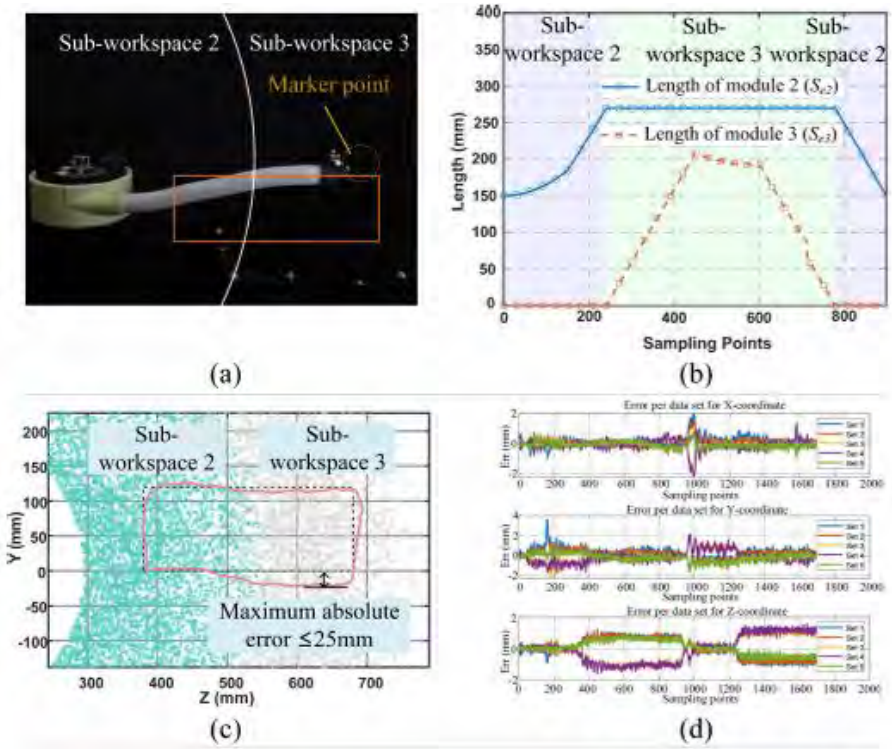

Fig. 10. Motion path experiment across different sub-workspaces. (a) Experimental setup. (b) Deployed arm length of each module. (c) Visualization of the absolute error. (d) Visualization of the repeatability error.

How NOKOV Contributes to the Research

The objective of this experiment is to verify the robot's ability to navigate across different subworkspaces by using the proposed variable kinematics motion control framework. Additionally, the positioning accuracy of the end-effector is also evaluated. As illustrated in Fig. 10(a), the robot was traversing a rectangular path (120 mm by 300 mm) spanning two subworkspaces, designated as subworkspace 2 and 3. Subworkspace 2 corresponds to the configuration with two modules deployed outside the robot case, while subworkspace 3 corresponds to the configuration with three modules outside. Optical markers were attached to the tip of the robot, and a NOKOV motion capture system (Mars 1.3H, 3D positioning accuracy ±0.2 mm) was used to record the actual path of the arm tip.

Citation Yuan P, Sun C, Chang X, et al. Design of a Deployable Continuum Robot (DCR) With Coiling Mechanism[J]. IEEE/ASME Transactions on Mechatronics, 2025.

Link https://ieeexplore.ieee.org/document/11026100

Disturbance Observer-Based Finite-Time Control Algorithm for Robotic Bolt-Tightening via Visual Feedback

Keywords

Power transmission tower, visual feedback, bolt-tightening robot, finite-time control, disturbance observer

Abstract

The increasingly mature visual feedback technology has greatly promoted the development of high-altitude unmanned operations, particularly in bolt-tightening operations for the power transmission tower. Nevertheless, traditional control algorithms relying on visual feedback encounter specific difficulties and challenges during bolt-tightening tasks execution. This paper presents a disturbance observer-based finite-time control algorithm to reject disturbances during bolt-tightening operations and mechanical errors inherent to the robotic system. Through theoretical analysis of this algorithm, based on visual feedback technology and the finite-time control method, the finite-time stability of the overall closed-loop system is ensured. Both the simulation and experimental results are given to validate the feasibility of the proposed control method. Compared with traditional PID, LQR, and MPC controllers, the convergence speed is increased by more than 16%, and the accuracy of steady-state error is also increased by more than 22%, moreover, the success rate is as high as 98%. It is highlighted that the proposed control method has superior disturbance rejection capability, faster convergence speed, and better reliability. Note to Practitioners—This study addresses challenges in visual feedback-dependent bolt-tightening operations for power transmission towers. A novel disturbance observer-based finite-time control algorithm is introduced, ensuring the stability of the closed-loop system. The method excels in rejecting disturbances and minimizing mechanical errors during bolt-tightening tasks. The simulation and experimental results confirm its superiority over conventional controllers in terms of disturbance rejection, convergence rate, and operational precision. Practitioners should consider the algorithm's potential to enhance the efficiency and reliability of bolt-tightening in high-altitude unmanned operations.

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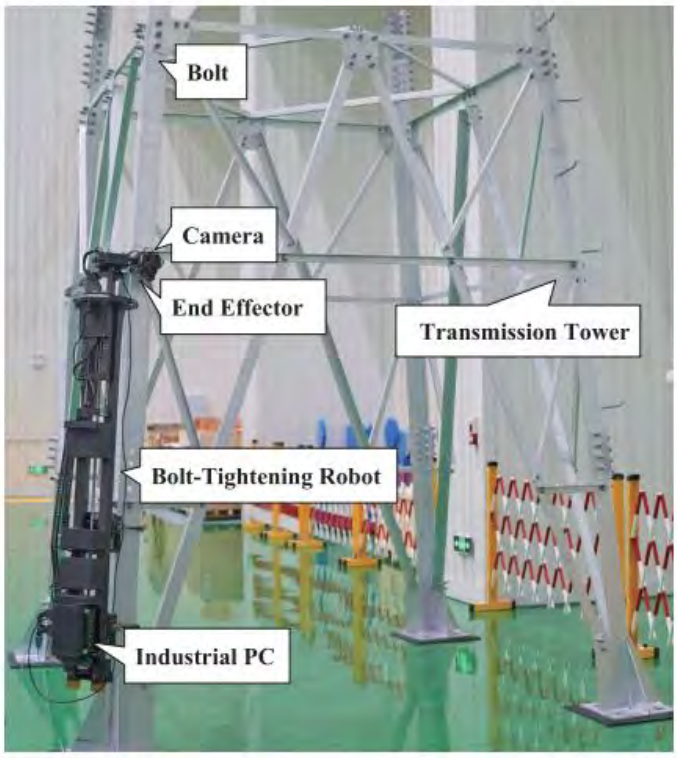

Fig. 5. The bolt-tightening robot experiment platform.

How NOKOV Contributes to the Research

To verify the accuracy of bolt recognition, this paper utilizes the Nokov optical 3D motion capture system, which has a recognition error controlled within ±0.01 mm. Therefore, the identified bolt position can be regarded as the ground truth for the target bolt.

Citation You J, Du H, Chen C C, et al. Disturbance Observer-Based Finite-Time Control Algorithm for Robotic Bolt-Tightening via Visual Feedback[J]. IEEE Transactions on Automation Science and Engineering, 2024.

Link https://ieeexplore.ieee.org/abstract/document/10691938

Edge-Aided Multi-Modal Collaborative SLAM for Resource-Constrained Underground Robots

Keywords

multi-modal SLAM, edge-aided, uncertainty minimizing, fusion pose graph

Abstract

Simultaneous localization and mapping (SLAM) of coal mine robots (CMRs) have become inevitable for monitoring, rescue, and transportation in coal mines. However, low illumination and single structures inevitably lead to sensors degradation in mine tunnels. Multi-modal fusion SLAM offers sensing complements but aggravates the consumption of computing resources, which is a huge challenge for CMRs with resource constrained memory and processors. In this paper, we design and deploy an edge-aided multi-modal collaborative SLAM algorithm (EM-CoSLAM) with LiDAR-inertial-visual fusion for constrained CMRs. EM-CoSLAM provides real-time mobile LiDAR tracking and precise edge visual optimization in parallel by decoupling and restructuring task modules. To reduce end-to-end latency and enhance system performance, EM-CoSLAM devises an adaptive offloading strategy to determine the optimal image frame by minimizing the pose uncertainty and further proposes a fusion pose graph optimization method. We completely implement EM-CoSLAM on the CMR and extensively evaluate it in various datasets and scenarios. The results indicate that EM-CoSLAM can achieve 6.7cm and 16fps performance on the CMR, outperforming existing solutions by more than 14%.

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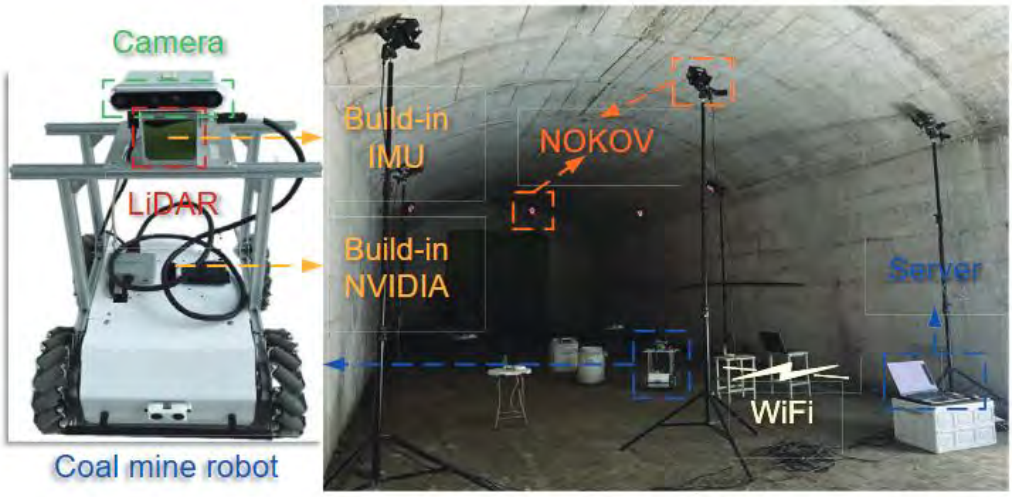

Fig. 11. The coal mine robot platform for EM-CoSLAM and the mine tunnel scene for data collection.

How NOKOV Contributes to the Research

Ground Truth Acquisition. In order to verify the accuracy of EM-CoSLAM, we use the optical 3D motion capture system (NOKOV) to obtain the ground truth of the CMR. We calculate the relative localization errors based on the sub-millimeter level accuracy provided by the NOKOV system to evaluate the performance of EM-CoSLAM.

Citation Zhang K, Gao S, Chen P, et al. Edge-Aided Multi-Modal Collaborative SLAM for Resource-Constrained Underground Robots[C]//IEEE INFOCOM 2025-IEEE Conference on Computer Communications. IEEE, 2025: 1-10.

Link https://ieeexplore.ieee.org/document/11044723

Kinetostatic Modeling of Retractable and Prismatic Spring Body for Continuum Climbing Robots in Discontinuous Terrains

Keywords

Mechanics modeling, prismatic spring, equivalent stiffness, cosserat-rod, continuum climbing robot

Abstract

There are few studies on the mechanics of the retractable backbone for continuum climbing robots, especially the non-circular cross-section. The retractable non-circular structure endows the robot with more compact structure, adjustability in initial stiffness, and dexterous mobility in narrow space. Consequently, a retractable prismatic spring backbone is proposed. Aiming at rectangular helical characteristic and coupling deformation, the backbone is equivalent to an elastic beam, whose equivalent stiffness is solved by the projection principle of the micro-segment deformation. Then the finite piecewise method and continuous differential method are used to establish its mechanical model. The piecewise method uses linear superposition principle to decouple the compression and bending deformation, and the rotation angle is solved by using the projection principle of the bending deformation. The continuous method uses the Cosserat-rod theory to establish the variable-curvature mechanics based on the equivalent beam, whose boundary-value problem is solved by gradually extending the integral region. Finally, two theory methods are in good agreement with FEA and experiment results; the continuous method has higher accuracy and piecewise method has lower computation cost; a multipurpose continuum climbing robot composed of the spring backbone, rotatable joint and flexible claw is applied to inspection in enclosed equipment.

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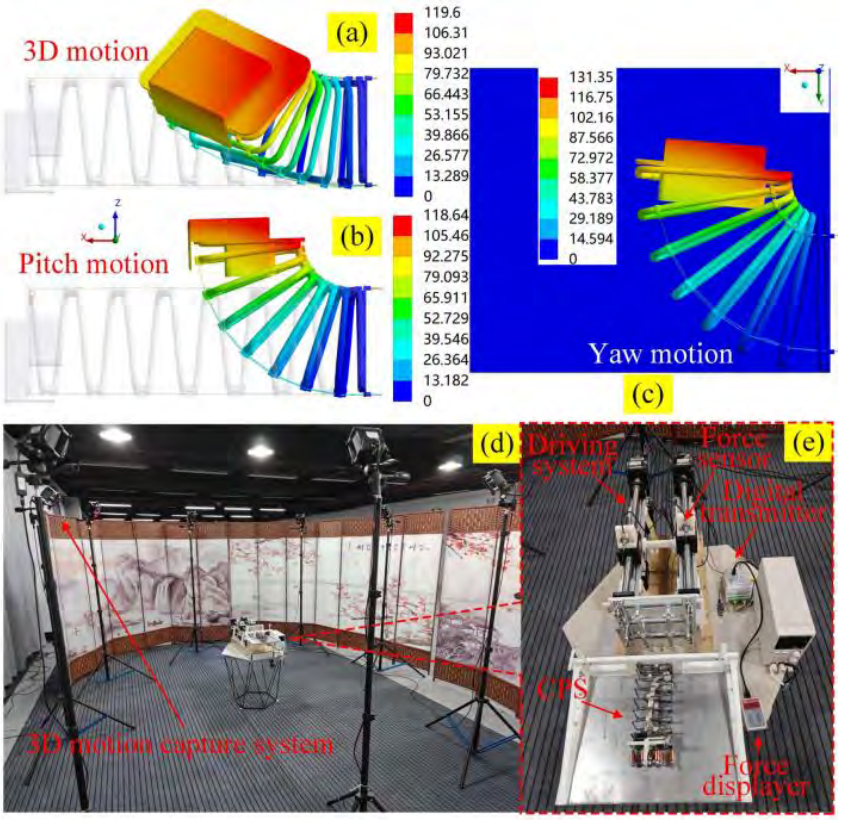

Fig. 5. (Top) Simulation deformation of the CPS. (a) 3D motion; (b) Pitch motion; (c) Yaw motion. (Bottom) Experiment setup. (d) Whole experimental

How NOKOV Contributes to the Research

Fig. 5(d) shows that whole experiment platform consists of the 3D motion capture system (NOKOV), the driving system, and the force-sensing system. The motion capture system accurately measures the 3D coordinates of reflective markers arranged on the backbone. The driving force is collected by corresponding force sensor, and digital transmitter transfer the data to force displayer in Fig. 5(e).

Citation P. Yang, J. Zang, G. Jin, J. Long, B. Huang and J. Zhao, "Kinetostatic Modeling of Retractable and Prismatic Spring Body for Continuum Climbing Robots in Discontinuous Terrains," in IEEE Robotics and Automation Letters, vol. 9, no. 12, pp. 10954-10961, De

Link https://webofscience.clarivate.cn/wos/woscc/full-record/WOS:001346123500015

Length-variable bionic continuum robot with millimeter-scale diameter and compliant driving force

Keywords

Bionic robot, continuum robots (CRs), robot design, soft drive

Abstract

Compared with conventional rigid-link robots, bionic continuum robots (CRs) show great potential in unstructured environments because of their adaptivity and continuous deformation ability. However, designing a CR to achieve miniaturization, variable length and compliant driving force remains a challenge. Here, inspired by the earthworm in nature, we report a length-variable bionic CR with millimeter-scale diameter and compliant driving force. The CR consists of two main components: the robot body and soft drives. The robot body is only 6 mm in diameter, and is composed of a backbone and transmission devices. The backbone is divided into three segments, and each segment is capable of adjusting its length and bending like the earthworm. The maximum length variation of the backbone can reach an astonishing 70 mm with a backbone's initial length of 150 mm, and the maximum bending angle of each segment can reach 120 degrees. In addition, we develop soft drives using pneumatic soft actuators (PSAs) as a replacement for the rigid motors typically used in conventional CRs. These soft drives control the motions of the transmission devices, enabling length variation and bending of the backbone. By utilizing these soft drives, we ensure that the robot body has a compliant driving force, which addresses users' concerns about human safety during interactions. In practical applications, we prove that this CR can perform delicate manipulations by successfully completing writing tasks. Additionally, we show its application value for detections and medical treatments by entering the narrow tube and the oral.

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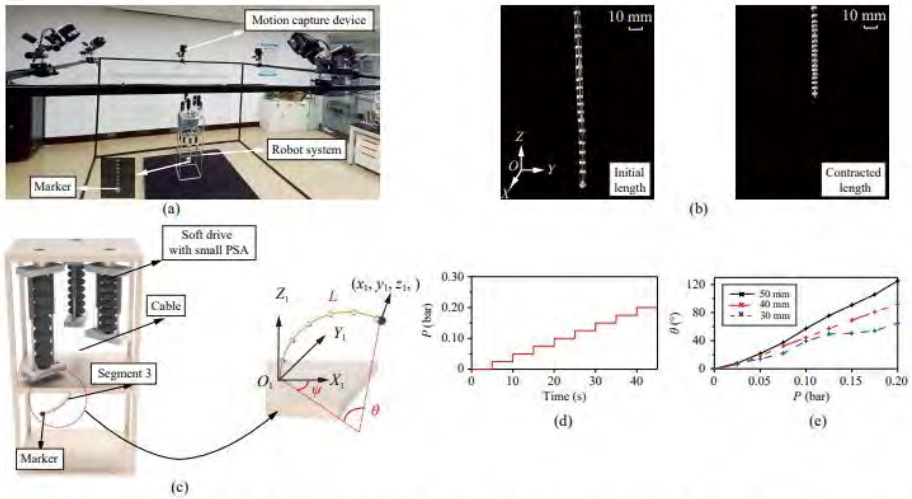

Fig. 6. Experimental platforms and results for the length variation test and bending performance tests of the designed CR. (a) Experimental platform for length variation test. (b) Initial length and contracted length of the backbone. (c) Experimental platform for bending performance tests. (d) Input pressure for a soft drive with small PSA of the segment 3. (e) Bending angles of the segment 3 under different segment lengths.

How NOKOV Contributes to the Research

The designed CR utilizes a motion capture platform composed of six infrared cameras (Model number: Mars 2H; Manufacturer: NOKOV; Accuracy: ± 0.15 mm; Frame rate: 380 FPS) to obtain the position information of the robot body's endpoint. A reflective marker (Model number: OH-CS12L-50; Manufacturer: NOKOV) is affixed to the endpoint requiring measurement. The marker moves in the three-dimensional space, and is tracked by the six infrared cameras, enabling the accurate measurement of its position.

Citation Zhao S, Meng Q, Lai X, et al. Length-variable bionic continuum robot with millimeter-scale diameter and compliant driving force[J]. IEEE/CAA Journal of Automatica Sinica, 2025.

Link https://ieeexplore.ieee.org/document/10869297

Model-Based Trajectory Planning of a Hybrid Robot for Powerline Inspection

Keywords

Distributed localization, privacy preservation, wireless sensor network (WSN)

Abstract

Effectively determining the accurate locations of sensor nodes while preserving data privacy is an interesting and challenging problem in the research of wireless sensor networks. On the basis of the well-performing distributed iterative localization framework in wireless sensor networks, this article proposes a dual privacy-preserving scheme based on node-intermittent updates and noises injection. A comprehensive analysis of the localization algorithm in terms of convergence and privacy-preserving performance is presented. It is theoretically demonstrated that the localization algorithm can achieve global accurate localization without leaking the privacy information of sensor nodes. At last, the performance of the privacy-preserving localization algorithm is verified by building an experimental platform containing six robots.

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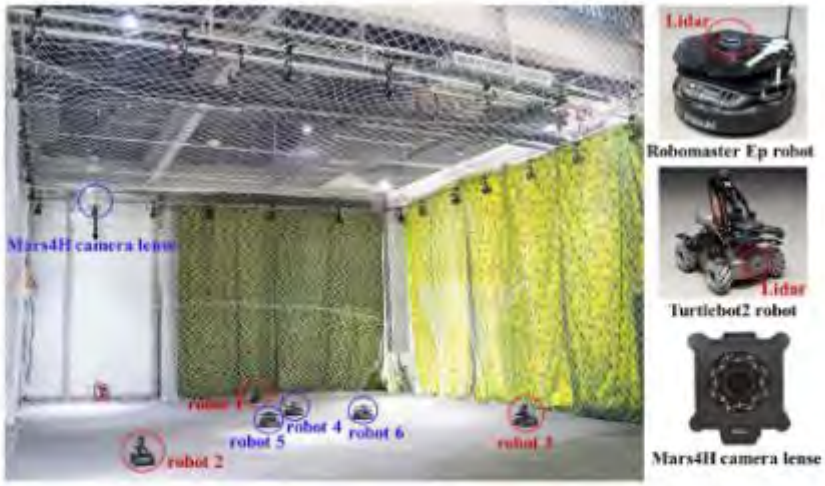

Fig. 3. Experimental platform composed of six robots and an NOKOV optical 3-D motion capture system, where robots 1,2,3 are the anchor nodes and robots 4,5,6 are the nonanchor nodes.

How NOKOV Contributes to the Research

The robots are randomly deployed over a 10 × 10 m2 square area, which is covered by a NOKOV optical 3-D motion capture system composed of 24 Mars4H camera lenses. Fig. 4 shows the robots' deployment and the motion capture system's coverage. The motion capture system can provide submillimeter level location data. In the 2-D space, each robot i's accurate location is decomposed into xi = (x1, x2). By the motion capture system, we can acquire all robots' accurate locations, i.e.

Citation Z. Li et al., "Model-Based Trajectory Planning of a Hybrid Robot for Powerline Inspection," in IEEE Robotics and Automation Letters, vol. 9, no. 4, pp. 3443-3450, April 2024, doi: 10.1109/LRA.2024.3363535.

Link https://ieeexplore.ieee.org/abstract/document/10423842

TDOA based localization mechanism for the UAV positioning in dark and confined environments

Keywords

Unmanned Aerial Vehicles (UAVs), Ultra-wideband (UWB), Inertial Measurement Unit (IMU), Time Difference of Arrival (TDOA), Autonomous inspection

Abstract

With the growing demand for autonomous inspection with Unmanned Aerial Vehicles (UAVs) in dark and confined environments, accurately determining UAV position has become crucial. The Ultra-Wideband (UWB) localization technology offers a promising solution by overcoming challenges posed by signal obstruction, low illumination condition, and confined spaces. However, conventional UWB-based positioning suffers from performance oscillations due to measurement inconsistencies and degradations with time-varying noise models. Furthermore, the widely used Two-Way Time-of-Flight (TW-TOF) method has limitations, such as high energy consumption and a restricted number of tags to be deployed. To address these, a sensor fusion approach combining UWB and Inertial Measurement Unit (IMU) measurements with Time Difference of Arrival (TDOA) localization mechanism is proposed. This method exploits an adaptive Kalman filter, which dynamically adjusts to noise model variations and employs individual weighting factors for each anchor node, enhancing stability and robustness in challenging environments. The comprehensive experiments demonstrate the proposed algorithm achieves a median positioning error of 0.110 m, a 90th percentile error of 0.232 m, and an average standard deviation of 0.075 m with the significantly reduced energy consumption. Additionally, due to TDOA communication principles, this method supports multiple tag nodes, making it ideal for multi-UAV collaborative inspections in future applications.

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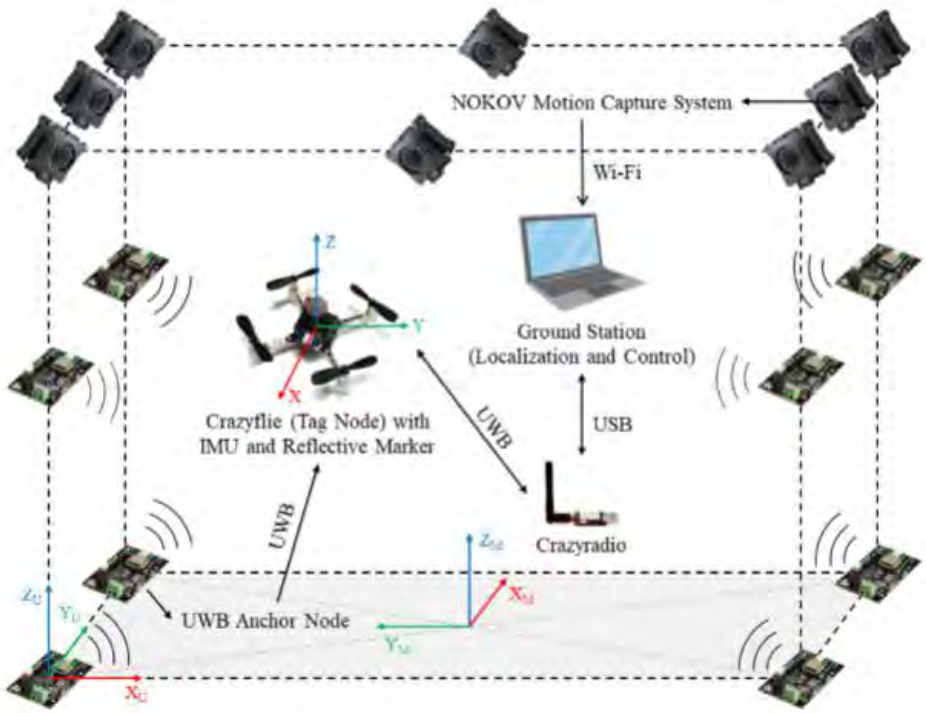

Fig. 1. System structure.

How NOKOV Contributes to the Research

> *3\. System structure*
> *The entire system, as depicted in Fig. 1, consists of five key compo.nents: one UWB tag node (the Crazyflie drone, which is equipped withan Inertial Measurement Unit (IMU) and a reflective marker), eightUWB anchor nodes, Crazyradio communication modules, a GroundStation, and the NOKOV Motion Capture System \[38]. Together, thesecomponents work seamlessly to achieve precise localization of the tagnode in a 3D space. Each component plays a critical role in ensuringthe overall functionality and accuracy of the system.*

Citation Shi H, Wang Q, Wang Z, et al. TDOA based localization mechanism for the UAV positioning in dark and confined environments[J]. Displays, 2026: 103346.

Link

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T-Timespan Dynamic Coverage of Mobile Camera Network for Visual Inspection

Keywords

Sensor Networks, Multi-Robot Systems

Abstract

Visual inspection by robotics and automation is widely applied in industry and daily life. Although dynamic coverage of mobile sensors has been developed for various tasks, existing methods are not suitable for visual inspection since sensing model is not taken into account. For this reason, this letter aims at investigating dynamic coverage of mobile camera network by fully analyzing and utilizing the sensing model of cameras. Moreover, we also consider the sustainability of the coverage by defining a new concept of T-timespan dynamic coverage, which deems that the coverage is maintained for a T timespan. A homeomorphic based visual distance is applied to describe the coverage performance of the camera with considering its anisotropic sensing property, and based on which the cost function representing the total coverage performance of the mobile camera network is constructed. The gradient based control algorithms are designed for mobile cameras with non-holonomic kinematics to maximize the cost function. The simulations are conducted to validate the proposed method for T-timespan dynamic coverage of mobile camera network, and the experiments show the application for visual inspection.

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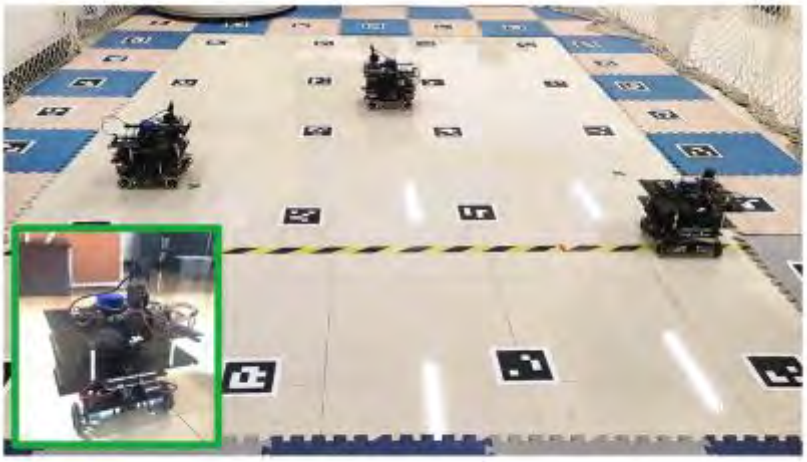

Fig. 6. UGVs with cameras and the experiment platform.

How NOKOV Contributes to the Research

A real experiment is designed in this subsection for visualinspection. In the experiment,N=3cameras mounted on theUGVs are estimated for the visual inspection whose the goal isto maximize theT-timespan covered area of a3 × 5m plane. A motion capture system from NOKOV Co. is installed aroundthe target area for the localizations of the UGVs in indoor environment.

Citation Chen X, Lei Z, Chen Y, et al. T-Timespan Dynamic Coverage of Mobile Camera Network for Visual Inspection[J]. IEEE Robotics and Automation Letters, 2023, 8(12): 8287-8294.

Link https://ieeexplore.ieee.org/abstract/document/10295971

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UAV Localization with Unreliable Observations in Hostile Underground Environments

Keywords

unmanned aerial vehicle (UAV) localization, Kalman filter, ultra-wideband (UWB) observation, hostile underground environment

Abstract

The accurate and robust unmanned aerial vehicle (UAV) localization is significant due to the requirements of safety-critical monitoring and emergency wireless communication in hostile underground environments. Existing range-based localization approaches fundamentally rely on the assumption that the environment is relatively ideal, which enables a precise range for localization. However, radio propagation in the underground environments may be dramatically influenced by various equipments, obstacles, and ambient noises. In this case, inaccurate range measurements and intermittent ranging failures inevitably occur, which leads to severe localization performance degradation. To address the challenges, a novel UAV localization scheme is proposed in this paper, which can effectively handle unreliable observations in hostile underground environments. We first propose an adaptive extended Kalman filter (EKF) based on the fusion of ultra-wideband (UWB) and inertial measurement unit (IMU) to detect and adjust the inaccurate range measurements. Aiming to deal with intermittent ranging failures, we further design the constraint condition by limiting the system state. Specifically, the auto-regressive model is proposed to implement the localization in the ranging blind areas by reconstructing the lost measurements. Finally, extensive simulations have been conducted to verify the effectiveness. We carry out field experiments in an underground garage and a coal mine based on P440 UWB sensors. Results show that the localization accuracy is improved by 16.9% compared with the recent methods in the hostile underground environments.

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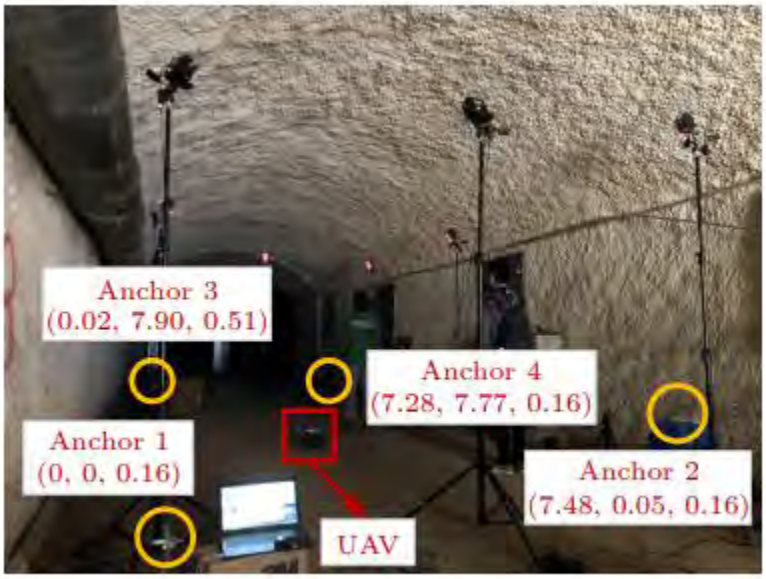

Fig.11. Underground coal mine scene.

How NOKOV Contributes to the Research

Since the ground truth of localization cannot be obtained directly in experiments, the NOKOV motion capture system with eight cameras is utilized to provide a 100 Hz sampling frequency of ground truth.

Citation Chen P P, Zhang K Y, Gao S W, et al. UAV Localization with Unreliable Observations in Hostile Underground Environments[J]. Journal of Computer Science and Technology, 2024, 39(6): 1401-1418.

Link https://link.springer.com/article/10.1007/s11390-024-3020-0

Vision-Based Autonomous Landing of a Hybrid Robot on a Powerline

Abstract

In recent years, various types of inspection robots have been developed to automate powerline inspection. The hybrid robot combines the advantages of climbing and flying robots and has a promising prospect in powerline inspection. But landing a hybrid robot on the target powerline among multiple ones is challenging. Flights require robust detection of powerlines and stable tracking of the target powerline. We propose a complete solution for the autonomous landing of a hybrid robot on a powerline. First, a special feature extraction operator and the corresponding density-based feature recognition algorithm are designed to detect multiscale powerlines. Second, a binocular vision-based depth estimation method for the landing point in the powerline is described. Third, two spatio-temporal dictionaries are established to track the target one in multiple powerlines. Meanwhile, landing strategies and control methods are presented to achieve a stable landing task. Finally, a hybrid robot is designed to validate the proposed method. The experiment results demonstrate the accuracy of the powerline detection and depth estimation algorithm, as well as the effectiveness of the robot in tracking and landing tasks.

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How NOKOV Contributes to the Research

Depth accuracy is crucial for the landing task. An optical NOKOV Mocap was used to evaluate the accuracy of the proposed ranging method. Fig. 11 shows the relative height between the powerline and camera measured by our method and Mocap, respectively. Since the measurement accuracy of the stereo camera decreases with distance, we divide the measurements into four intervals to calculate the errors, respectively. The results of the data analysis are shown in Table II. When the depth is less than 0.8 m, the mean absolute error (MAE), root mean squared error (RMSE) and max error are less than 5.09, 6.38, and 18.05 mm, respectively. Considering the margin brought by the guiding mechanism, the depth accuracy can meet the requirements of the actual landing task.

Citation Li Z, Tian Y, Yang G, et al. Vision-based autonomous landing of a hybrid robot on a powerline[J]. IEEE Transactions on Instrumentation and Measurement, 2022, 72: 1-11.

Link https://ieeexplore.ieee.org/search/searchresult.jsp?newsearch=true&queryText=Vision-Based%20Autonomous%20Landing%20of%20a%20Hybrid%20Robot%20on%20a%20Powerline

分布式线-气协同驱动连续体机械臂机构及控制研究

关键词

连续体机械臂;协同驱动;变刚度;形状重建;闭环控制;逆运动学;

摘要

连续体机械臂凭借其高柔顺构型、多自由度运动学特征及非结构化环境适应机制,发展成为工业密闭空间检测、航天维修和灾难救援等领域的重要技术解决方案。与此同时,狭小、密闭及非结构化环境对连续体机械臂的工作空间范围、变刚度和位置控制等研究方向提出严峻挑战。目前已有连续体机械臂很少能兼顾可伸缩和变刚度特性来提高其工作空间和负载能力。此外,连续体机械臂的位置反馈多依赖双目视觉、磁场和动作捕捉系统等外部感知方法,限制了其在狭小空间场景的应用。因此,本文开展连续体机械臂的可伸缩可变刚度、本体形状感知和末端点位置闭环控制的研究工作,从而解决上述问题。通过结合线驱动精准定位和气驱动柔顺调控的优势,本文提出线-气协同驱动方案,设计了一款兼具可伸缩与变刚度特性的连续体机械臂。在此结构基础之上,设计制备硅橡胶软传感器,建立本体形状感知系统,实现连续体机械臂末端点位置和形状的实时重建。然后,借助运动学模型、本体形状感知系统和闭环控制算法实现连续体机械臂的末端点轨迹控制,主要研究内容如下: 针对连续体机械臂作业空间受限和刚度性能低的问题,本文基于螺旋结构并结合软体气动驱动器提出一种可伸缩变刚度连续体机械臂。线、气驱动分别作用时,连续体机械臂实现缩短和伸长功能,而当驱动线拉力和软气腔推力相互拮抗作用时,能够改变连续体机械臂的刚度。本文还构建了线-气协同驱动静力学模型,在已知驱动力和外部载荷下,通过四阶龙格-库塔法和打靶法,能够得到连续体机械臂的变形形状。在力学模型中,分析了驱动线路径偏移、摩擦力及刚度增益对末端点精度的影响,实现力学模型的准确表征,为多段式连续体机械臂的结构参数设计提供理论依据。 针对多段式连续体机械臂的运动控制问题,本文建立三段式连续体机械臂的运动学模型。其中,对同一目标点不同构型空间的问题,本文采用等效虚拟连杆方法,建立其逆运动学模型。通过对弯曲角度和旋转角度的约束,建立末端轨迹优化算法,从求解效率、末端定位精度和运动平滑性三个维度对其进行评估,使机械臂保持本体形状变化连续的同时实现末端点目标轨迹的跟踪。 针对连续体机械臂本体形状感知问题,本文基于所设计的硅橡胶应变传感器提出可伸缩连续体机械臂形状重建方法。其核心是通过测量本体特定位置的应变,进行多传感器信息融合,建立形变-曲率映射关系,实现本体形状重建。针对用于臂形感知的传感器,本文制备了一款细长型电容式软传感器,其便于安装且具备重复性高、滞后小、线性度高、伸长率大等优异性能。然后,采用分段常曲率模型假设,并考虑本体扭转变形的现象,建立了本体形状感知的理论模型,实现连续体机械臂形状实时重建功能。 针对机械臂末端点的精准控制问题,本文以本体形状感知系统的末端点位置信息作为反馈,基于微分运动学模型,建立线驱动末端点位置闭环控制模型。然后,针对线驱动无法调控中心曲线延伸的问题,本文建立前馈反馈复合的线-气协同位置闭环控制模型。通过

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搭建两个模块串联组成的单段连续体机械臂,绘制了"HIT"字形轨迹,对控制器中位置误差调控时间进行分析。此外,本文进行三段式连续体机械臂末端点的偏心圆轨迹控制,在本体形状感知系统、闭环控制模型和逆运动学算法的集成框架下,末端点的平均位置误差与机械臂长度之比仅 0.9%。最后,搭建了基于形状优化算法的控制框架,实现连续体机械臂进入作业环境过程的形状控制。

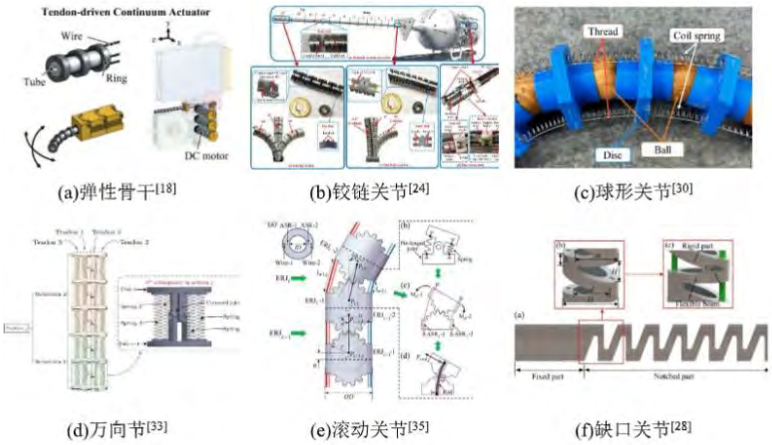

图 1-1 线驱动连续体机械臂的关节结构

NOKOV 度量动作捕捉在研究中的应用摘录

> *4.6 本体形状感知模型实验验证*
> *4.6.1 单个模块形状感知验证*
> *为了验证常曲率本体形状感知模型的准确性，搭建如图 4-8 所示实验测试平台。该平台主要包括连续体机械臂驱动系统、本体形状感知传感系统（采样率 100Hz）和运动捕捉系统。*
> *通过控制三根驱动线丝的运动，实现连续体机械臂本体变形。驱动线分别由三组直线导轨引导。采用线鞘形式的驱动机构，可以通过长而灵活弯曲的通道提供远程力和运动传递。这种驱动方法有效避免了对传输力结构设计的需要。本体感觉系统主要由九根可拉伸圆柱形电容传感器、一个信号采集卡和一个 NI 实时机组成。每根软传感器跨越三个节距长度，被固定在连续体机械臂的两端，而它的中间部分被允许在一个受限的孔径内自由滑动。安装在连续体机械臂上标记物的真实位置，可通过运动捕捉系统（由北京 NOKOV 科技有限公司开发，配备分布在连续体机械臂周围的 8 个 Mars 2H 透镜）计算得到。*

引用格式 王鹏远.分布式线-气协同驱动连续体机械臂机构及控制研究[D].哈尔滨工业大学,2025.DOI:10.27061/d.cnki.ghgdu.2025.000320.

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基于众数频数优化的多机器人弹性协同持续监测路径规划

关键词

多机器人；持续监测；路径随机性；麻雀搜索算法；弹性规划

摘要

多机器人系统在地面侦察、环境监测及重点区域巡逻等应用中展现出显著优 势。然而，在多机器人协同领域，由于周期性的监测路径容易导致监测规律的泄露， 很容易被外界伺机破坏，因此增加机器人监测路径的随机性有助于提高系统的监 测性能。本文对多机器人持续监测系统路径规划问题展开研究，主要工作如下： 从节点的监测频率和监测路径的随机性两个方面考虑，以节点的最小访问次 数以及最小节点访问周期众数频数的比值为优化目标函数，建立多机器人持续监 测路径规划模型。为了寻找模型的解决方案，提出了自适应变异麻雀搜索算法，在 简单和复杂路网上的仿真，成功得到了高随机性的机器人巡逻路径。与其他传统算 法比较，麻雀搜索算法具有更快的搜索速度。 考虑机器人可能发生故障的情况，通过最大化故障后剩余机器人路径的最小 节点访问次数以及最小节点访问周期众数频数的比值，建立多机器人弹性持续监 测路径规划模型。然后，采用仿真实验验证了新的目标函数在弹性路径规划问题中 的有效性。 开展了室内环境中多机器人持续监测系统的路径规划实验，通过将仿真和实 物实验得到的路径结果作对比分析，进一步验证了本文路径规划方法的可行性和 有效性。本文提出的方法为求解其他领域的多机器人持续监测路径规划问题提供 了理论支撑和经验参考。

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图 3.16 NOKOV 动作捕捉系统

NOKOV 度量动作捕捉在研究中的应用摘录

最后，在室内环境下，由于 GPS 无法为 UAV 提供定位服务，本文采用了 NOKOV 光学三维动作捕捉系统来替代。并构建了 HRDS 路径规划的三维场景，用于记录 UAV 的飞行轨迹。如图 3.16 所示，NOKOV 动捕系统是一种利用光学摄像头和传感器来追踪和记录物体或人体运动的技术。该系统能够提供非常精确的位置和姿态测量，适用于对准确性要求较高的应用场景。其设计考虑了光照变化、阴影和其他环境干扰，确保所提供的数据在各种条件下的可靠性。

引用格式 刘午虓.基于众数频数优化的多机器人弹性协同持续监测路径规划[D].武汉科技大学,2024.DOI:10.27380/d.cnki.gwkju.2024.000403.

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面向持续监测任务均衡的多无人机路径规划

关键词

无人机；持续监测；路径规划；任务均衡；不确定时间

摘要

持续监测任务需要对目标区域进行连续不间断的访问，以获取实时信息。当 监测环境存在硬性访问周期约束时，单架无人机难以满足监测要求，多无人机协 作是执行任务的首选。然而，不均衡的任务分配会危害无人机安全，甚至导致监 测任务失败。本文研究了面向持续监测任务均衡的多无人机路径规划问题，主要 工作如下： 首先，针对无人机飞行时间确定的情况，本文提出了等待因子和任务水平， 前者反映监测点等待被访问的紧迫程度，后者反映无人机任务难度。设计了蚁群 初始化的遗传算法用于规划单无人机路径，并提出基于任务水平改进的 K 均值聚类算法用于多无人机均衡性任务分配。仿真结果表明提出的算法能够为多无人机 求得均衡性路径规划。 接着，针对无人机飞行时间不确定的情况，本文假设飞行时间是服从已知正 态分布的随机变量，通过引入机会约束构造随机规划模型。在蚁群初始化的遗传 算法中加入了局部搜索，同时优化无人机使用数量和路径的均衡性。仿真结果表 明提出的算法能够获得执行监测任务所需的最少无人机数量和其对应监测飞行 路径。 最后，开展了室内环境下无人机模拟监测飞行的实物实验，通过对比分析仿 真和实物实验得到的路径结果，进一步验证了所提算法的可行性和有效性。本文 提出的方法对降低持续监测成本，提高监测频率，保障无人机安全具有重要意义。

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(a) 四旋翼无人机　　(b) 动作捕捉相机

图 5.3 实验设备介绍

NOKOV 度量动作捕捉在研究中的应用摘录

本文的实物实验采用了 Nokov 光学三维动作捕捉系统，在室内环境中对捕捉区域进行覆盖。该系统的硬件组成部分包括动作捕捉镜头、镜头固定装置、镜头连接线、POE hub 连接器、标定杆、反光标识点和电脑等。动作捕捉相机通过发射特定波长的红外光，实时精确捕捉贴在无人机表面的反光标志点的三维空间位置。随后，通过以太网将标志点的位置信息实时传输至地面端的工作站电脑。在电脑端运行动作捕捉软件，利用先进算法进行处理和运算，可以解算出不同时间单位上各个反光标志点的三维空间坐标，以及无人机的精确位置和姿态等三维数据，以供进一步的数据分析。

引用格式 詹欣茹.面向持续监测任务均衡的多无人机路径规划[D].武汉科技大学,2024.DOI:10.27380/d.cnki.gwkju.2024.000389.

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面向可靠性巡检的多无人机优化方法

关键词

可靠性工程；路径规划；遗传算法；贪婪算法

摘要

无人机具有视野开阔、隐蔽性好、效率高等优点，因此被广泛运用在自主监测领域。然而，有限的续航能力和易发生的各类故障严重削弱了无人机执行巡检任务的可靠性，而且损坏的无人机难以维修导致成本较高。为了提高无人机完成任务的可靠性并且降低巡检成本，本文研究面向可靠性巡检的无人机路径规划和无人机数量的优化方法。主要工作如下：

（1）提出了一种面向可靠性巡检的多无人机路径规划方法。通过协调无人机组飞行路径，使得同一任务点能被不同无人机巡检，达到提高可靠性的目的。建立了多无人机协作巡检路径规划模型，并且基于贪婪策略设计了三步优化求解方法。仿真结果表明，所提方法不仅可以提高巡检任务完成的可靠性，而且能有效地提高完成巡检任务的快速性。

（2）由于无人机发生故障时维修困难，若能选择较少数量的无人机完成给定的巡检任务，则可以达到控制成本的目的。本文针对无人机经济性优化问题，首先建立了无人机数量与任务完成率之间的关联模型，然后，结合遗传算法与贪婪算法，提出了采用三步法优化无人机的数量和路径。仿真结果表明，本文提出的方法能找到满足任务完成率要求所花费最少的无人机数量。

（3）对所提的方法进行物理实验验证。实验结果表明本文的方法在实际巡检任务中有效可行。

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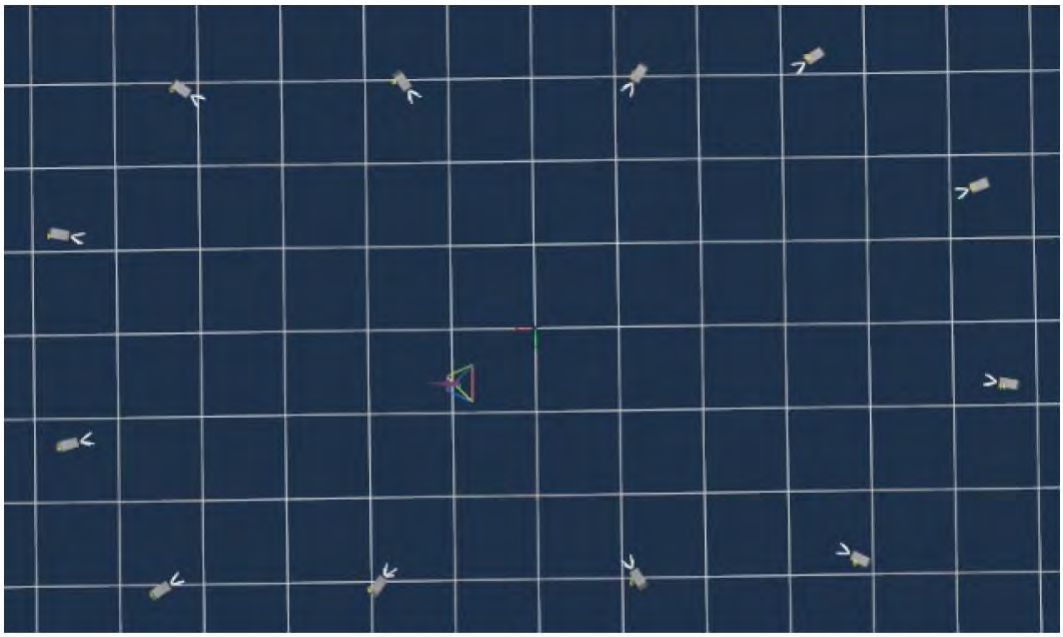

图 5.2 实验环境

NOKOV 度量动作捕捉在研究中的应用摘录

本文使用的动补系统为 NOKOV（度量）光学三维动作捕捉系统，实物环境如图 5.2 所示，图中四散的十二个银色标志为摄像头，彩色三角架为无人机，无人机从起点出发，在摄像头围成的小型区域中执行巡检任务，通过摄像头对无人机三维位置进行定位，然后实时捕捉无人机的飞行路径并上传至电脑。

引用格式 王奕澍.面向可靠性巡检的多无人机优化方法[D].武汉科技大学，2023.DOI：10.27380/d.cnki.gwkju.2023.000755.

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面向空地两栖机器人的多传感器融合 SLAM 系统

关键词

同步定位与建图;空地两栖机器人;多传感器融合;非线性优化;

摘要

空地两栖机器人凭借双模态运动特性在灾难救援、设施巡检等应用场景中展现出卓越的适应性与灵活性,而这种独特的运动模式与机械构型也给其自主定位带来了特有的挑战,例如飞行模式与地面模式之间显著的视野差异、模式切换过程中的运动冲击,以及地面行驶时的姿态不稳定等问题。传统视觉 SLAM 难以高效地应用于空地两栖机器人,精准鲁棒的定位技术成为阻碍其工程化应用的技术瓶颈。针对上述挑战,本文提出了一个适用于空地两栖机器人的 SLAM 系统,具体研究内容如下: 提出了一个融合视觉相机、IMU、编码器、单点激光测距传感器的环境感知增强 EAR-SLAM 系统。其中,设计了一个地形感知里程计模型,该模型能够估计局部地形坡度,并通过速度校正和速度方向识别,准确获取机器人在三维空间中的真实运动矢量,解决了空地两栖机器人在地面模式下视觉惯性里程计退化和传统轮式里程计失效的问题;设计了一种传感器异常感知与权重调整方法,在线诊断视觉退化、车轮打滑等异常,动态调整相关传感器在融合优化中的权重,并部署了飞行状态感知模块,实现了机器人空-地模式的自主判别与鲁棒切换。构建了非线性优化框架集成边缘化先验约束、视觉重投影约束、IMU 预积分约束及地形感知里程计约束,这些不依赖视觉感知的传感器的有效利用为系统提供了额外的运动估计和状态约束,同时异常感知可以有效检测视觉匹配失败情况,有效应对了空地两栖机器人相机视野变化和视线遮挡带来的挑战。 为验证所提 EAR-SLAM 系统的有效性,搭建了实验平台,并完成了相机、IMU、编码器、单点激光测距传感器的选型、安装工作,分别测试了系统的定位精度与定位鲁棒性,在不同地形、空-地模式切换、视觉信息失效、轮子打滑等多种具有挑战性的真实环境中进行了广泛的实验,并针对所提的地形感知里程计模型和传感器异常感知与权重调整方法设计进行了消融实验。实验结果表明,相比传统的 VIO 方法,EAR-SLAM 在各类场景精度显著提升 39% ~ 83%,能够有效抑制 z 轴漂移和 VIO 退化。在视觉完全失效、严重丢帧、纯旋转、轮子空转等极端工况下,仍能维持稳定连续定位。消融实验表明,相比传统轮式里程计,地形感知里程计使精度平均提升约 50.9%;异常感知模块在传感器异常时使误差降低率达 20% ~ 90%。

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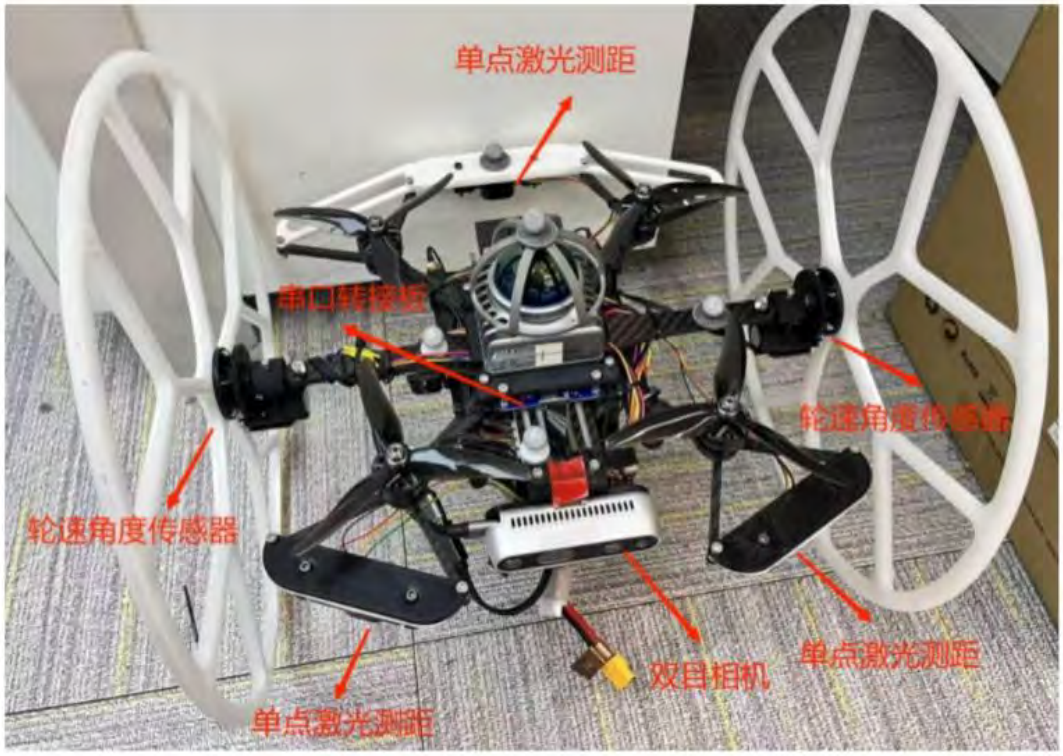

图 4.2 空地两栖机器人传感器安装示意图

NOKOV 度量动作捕捉在研究中的应用摘录

> *3、参考真值系统*
> *准确的性能评估依赖于高精度的真值参考。在本章实验中:*
> *(1)室内场景采用 NOKOV 光学动作捕捉系统。该系统通过多个红外相机跟踪机器人身上的标记点，能够提供毫米级的实时定位精度，作为室内实验的真值基准(2)室外场景采用 Livox Mid-360 激光雷达。通过运行高精度的激光 SLAM 算法 FAST-LIO2\[10]处理 LiDAR 数据，生成高精度的参考轨迹，作为室外实验的基准。*

引用格式 贺文君.面向空地两栖机器人的多传感器融合 SLAM 系统[D].哈尔滨工程大学,2025.DOI:10.27060/d.cnki.ghbcu.2025.000206.

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https://kns.cnki.net/kcms2/article/abstract?v=yqBhao7Q9gyuarJ_72OvR9clP_YUf-iN6xthCSZtz9ESKm6dX_qVh4mSn2rAMgNEIzc7f-13sHSr14L8IZZJl0i-09fDph2tN0y1dLx0LCwppBSMHVr1Z1sdjLePnyec7G2UrnPqMMYDDp9wEdmI2dO7OAwub5apdnGXIR8fkpbvVznoSU9-LA==&uniplatform=NZKPT&langua

面向立体巡检的无人机覆盖路径规划研究

关键词

覆盖路径规划；无人机；立体巡检；蚁群算法；K 均值聚类

摘要

无人机凭借机动性强、成本低廉、方便搭载各类传感器等优点被广泛应用于立体巡检任务，然而如何高效地规划无人机飞行路径仍是目前研究的难点。为解决该问题，本文将无人机三维覆盖路径规划问题划分为视图规划和路径规划两个子任务，并在路径规划任务中分别使用单无人机和多无人机完成路径搜索。

在视图规划中，本文提出了种基于尺均值聚类生成候选视点的方法，并使用概率势场法来生成对应视线，接着考虑距离约束和角度约束，创建可见性矩阵编码视点和三角形之间的可见性信息，然后构建候选视点互连的非完全图模型，将无人机三维覆盖路径规划问题转换成图搜索问题。

在单无人机覆盖路径规划研究中，本文以巡检覆盖率为约束，建立了以最小化路径长度、视点数目、急转弯次数的加权和为目标函数的单无人机覆盖路径规划模型，并提出了面向排序的混合蚁群算法完成单架无人机的最优路径搜索。仿真实验结果验证了模型和算法的有效性与可行性，同时与传统算法相比更优，在实际应用中具有可靠性。

在多无人机覆盖路径规划研究中，本文在存在静态障碍物的三维环境中，以巡检覆盖率和续航时间为约束，建立了以最小化多无人机系统的任务完成时间和均衡多无人机工作量为目标函数的多无人机覆盖路径规划模型，并采用面向排序的混合蚁群算法完成多架无人机的最优路径搜索。仿真结果验证了模型的准确性和算法的有效性。

本文提出的无人机三维覆盖路径规划方法解决了无人机在立体巡检领域面临的难题，为无人机在立体巡检领域的研究和应用提供了新的思路和方法。

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图 4.9 实验环境

NOKOV 度量动作捕捉在研究中的应用摘录

在实验中采用 NOKOV 光学三维动作捕捉系统获取无人机飞行过程中的位置和运动轨迹数据。该系统利用高性能红外镜头覆盖实验区域，并对标有反光标志点的目标进行精确的位置捕捉。经过先进算法的处理，该系统可以获取不同时间反光点的三维坐标值。

引用格式 陈丽.面向立体巡检的无人机覆盖路径规划研究[D].武汉科技大学，2023.DOI：10.27380/d.cnki.gwkju.2023.000891.

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https://kns.cnki.net/kcms2/article/abstract?v=DFdco8SIy0IP4DTj0fF0XTgmHScc8F-NNiE65-ZXzr8xvpR9gbFJq2AEvD6w0unxy6Q0iHpnk5OkUT_aR__FnE7v2MF5yTQGk1bz3ma2csR18ie7cj3HOg==&uniplatform=NZKPT&language=gb

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巡检机器人自主行走及巷道变形检测技术研究

关键词

巡检机器人；路径规划；自主行走；激光扫描；巷道变形检测

摘要

煤矿巷道的安全高效掘进在煤岩开采中起着十分重要的作用，但巷道环境复杂、安全隐患大，而使用传统的巷道变形检测方法效率低、耗时长，且需要人工深入现场测量，因此利用机器人参与煤矿巷道巡检工作是未来的发展方向。随着三维激光扫描技术的发展，激光雷达能够快速、准确的获取环境信息，被广泛应用于各行各业。因此，本文以移动巡检机器人为平台，通过搭载三维激光雷达，实现巡检机器人在巷道环境下的自主行走及巷道变形检测。具体内容如下：

(1)搭建了巡检机器人平台及系统模型。首先针对煤矿巷道的智能化检测进行需求分析，设计了基于履带式的移动巡检机器人实验平台，确定了巡检机器人的软硬件系统方案。然后根据系统的总体方案，针对性的建立巡检机器人的系统模型，为巡检机器人的运动控制和巷道环境扫描提供了基础。

(2)提出了基于改进 A\算法与 DWA 算法的混合路径规划方法并进行实验验证。首先以全局路径规划 A\算法为基础，针对传统 A\算法规划的路径拐点多、路径不平滑等问题，提出一种包含目标权重信息的改进启发函数，并基于 Floyd 算法和 B 样条曲线进行冗余节点的剔除及路径平滑处理。然后将全局路径规划 A\算法和局部路径规划 DWA 算法进行融合，提取出改进 A\算法的全局路径关键节点信息，将提取到的全局路径节点依次设置为 DWA 算法的局部目标点，进行动态路径规划至目标点。实验结果表明，本文所提融合改进 A\算法和 DWA 算法的混合路径规划方法效率更高、安全性更好，可以满足煤矿巷道巡检机器人的运动要求。

(3)研究了基于激光扫描的巷道变形检测关键技术。首先阐述了点云去噪以及下采样方法的工作原理，针对点云去噪以及下采样方法的不足，提出了融合统计滤波和中值滤波的点云去噪方法以及基于密度约束和重心临近点的体素化网格下采样方法。然后使用双向投影法提取巷道中轴线，利用 CloudCompare 点云处理软件分割点云数据，提取巷道断面并拟合轮廓曲线。最后介绍了依据已处理的点云数据提取巷道变形量，进行巷道变形检测与分析的方法。

(4)为验证整体方案的可行性，使用巡检机器人实验平台进行自主行走实验研究及巷道变形检测应用分析。首先依靠巡检机器人平台验证本文所提路径规划算法的性能及实际应用效果。然后对激光扫描获取的模拟巷道点云数据进行处理，提取变形量，进行巷道变形分析。

本论文包含图 58 幅，表 19 个，引用格式 115 篇。

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NOKOV 度量动作捕捉在研究中的应用摘录

利用 NOKOV 动作捕捉系统再次测量标志物所在的中心坐标。由于 NOKOV 动作捕捉系统采用高性能红外镜头，可以获取被捕捉物亚毫米级精度的三维坐标，因此可将其测量值视为真实坐标值。

引用格式 袁科文.巡检机器人自主行走及巷道变形检测技术研究[D].中国矿业大学，2023.DOI：10.27623/d.cnki.gzkyu.2023.002878.

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月面南极巡视器自主导航路径规划算法

关键词

月球南极; A 算法; DWA 算法; 高精度自主导航; 融合路径规划算法;

摘要

针对巡视器在月球南极弱通信条件下实现阴影区探测及自主采样返回等复杂任务时，对高精度自主导航系统的迫切需求，综合考虑巡视器安全保障及月面南极具有提升导航精度属性环境因素等，结合 A 算法构建的全局辅助路径与 DWA(Dynamic Window Approach)算法，提出一种实现巡视器高精度自主导航的融合路径规划算法（Landmark Integrated Path Planning Algorithm, LIPPA）。将激光雷达定位建图算法的定位精度作为评价指标，分别设置了数学仿真及半物理试验来验证本算法的可行性和在不同应用场景对提升巡视器导航精度的有效性。试验结果表明，巡视器沿着 LIPPA 规划的路径移动时，与单因素考量的传统路径规划算法相比，激光雷达定位建图算法在二维平面的平均绝对定位误差最大减少了 42%，可为月面南极复杂地貌环境下的自主导航与路径规划任务提供技术支撑。

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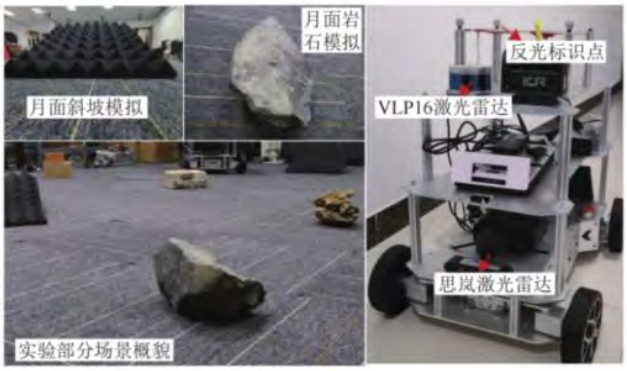

图 14　试验条件
Fig. 14　Experiment conditions

图 15　Nokov光学三维运动捕捉系统
Fig. 15　Nokov optical 3D motion capture system

NOKOV 度量动作捕捉在研究中的应用摘录

综合试验条件的限制及对试验效果的考量，选择在具有高精度动态捕捉系统的室内搭建半物理试验场景，利用石块来模拟月面岩石，并搭建斜坡来模拟月面南极起伏的地形。试验用到的 4 轮巡视器及室内试验场景如图 14 所示。巡视器搭载的主要器件：1 个思岚 2D 激光雷达，1 个 Velodyne 16 线激光雷达，3 个反光标识点，2 个装有基于 Ubuntu18.04 的 ROS Melodic 系统的控制器。同时，在室内试验场景部署了 Nokov 光学三维运动捕捉系统（共 12 个动作捕捉镜头），如图 15 所示。

引用格式 王慧婷，余萌，李昱叶等.月面南极巡视器自主导航路径规划算法[J].深空探测学报（中英文），2023,10（06）：598-607.DOI：10.15982/j.issn.2096-9287.2023.20230084.

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履带式换热器检测机器人设计

关键词

换热器检测;履带机器人;磁吸附;模型预测控制

摘要

换热器是石油化工、核能电力等工业领域实现流体热传递的关键设备，其中以碳钢材质换热器应用最为广泛。为保障换热器安全服役，本文提出一种履带式磁吸附检测机器人方案。首先，为应对管板开孔导致的非连续导磁表面，基于 Halbach 阵列原理设计了一种高性能永磁吸附模块，并通过有限元仿真验证了其吸附力与可靠性。其次，为减少履带磨损并提高行驶平顺性，提出一种基于 Reeds-Shepp 曲线的往复式路径规划方法。进一步，为克服竖直壁面作业时的重力滑移问题，设计了一种带有重力滑移补偿的改进模型预测控制策略。样机爬壁试验结果表明，该机器人能够在模拟管板表面稳定吸附，并精准跟踪规划路径，最大轨迹跟踪横向误差在直线段小于 3 mm、在曲线段小于 6 mm。本研究为换热器的自动化检测提供了切实可行的机器人解决方案。

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图 11 换热器检测机器人试验现场

NOKOV 度量动作捕捉在研究中的应用摘录

硬件主要由履带式磁吸机器人、分体式探头送给装置、NOKOV 光学动作捕捉系统、漏磁检测探头及上位机等组成。其中，机器人作为检测作业的移动载体，依托永磁吸附模块实现稳定附着。在定位环节中，系统借助外部光学动作捕捉相机，实时追踪安装在机器人顶部的无源红外反射标志点，由上位机软件完成机器人实时位姿的解算。在控制环节中，上位机基于路径规划结果，通过 LoRa 无线模块向机器人发送运动指令，并协同控制探头输送装置。机器人本体与输送装置之间通过柔性导管连接，在送给装置的驱动下，检测探头沿导管伸入换热管完成信号采集任务后自动收回。

引用格式 郑金城,兰雅婷,伍剑波,等.履带式换热器检测机器人设计[J].机械,2026,53(4):45-52.

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面向动态扩散污染源的多无人机协同寻源与边界测绘

关键词

动态污染源;多无人机;协同寻源;浓度分布预测;边界测绘;

摘要

针对高危工业场景中动态污染源位置未知、扩散分布时变、环境复杂等挑战，提出一种面向动态扩散污染源的多无人机协同寻源与边界测绘方法。首先，在寻源阶段，采用快速多点期望改进（F-EI）算法指导无人机高效采样，并使用结合动态窗口优化（DWO）与动态核宽度调节的径向基函数（RBF）预测模型对动态扩散污染源进行预测。其次，在边界测绘阶段，设计了融合间距误差反馈机制的滑模控制器，驱动无人机追踪动态等值线并在目标等值线上保持均匀环绕。最后，引入基于缓冲维诺单元（BVC）的约束机制，实现无人机动态避障与机间防碰。仿真与实验结果表明，所提算法能够快速构建污染分布模型，在动态变化环境下仍具有较好的鲁棒性。算法在感知精度、决策效率和执行安全三方面取得良好平衡，为高危场景下突发污染事件的实时监测与应急响应提供了可靠的技术支持。

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NOKOV 度量动作捕捉在研究中的应用摘录

4.1 实验环境\n 实验环境设置在 7m×7m 的室内飞行空间内，由 NOKOV 光学动作捕捉系统完全覆盖。图 14 中，飞行空间上方设置有 16 个动作捕捉相机，定位精度达到 ±1cm，可同时捕捉最少 12 个不同目标，用于提供无人机的定位信息。无人机为 RMIT 无人机，尺寸为 98 mm×92.5 mm×41 mm，搭载集成 ESP32 芯片的开源扩展模块作为核心运算单元，支持 2.4/5.8 GHz 双频通。为确保室内实验的安全性与编队稳定性，设置无人机的最大水平飞行速度为 0.5 m/s，最大偏航角速度为 1.0 rad/s，重量为 87 g，每架无人机搭载四个用于定位的反光球，适合在狭小的室内环境进行实验。

引用格式 曹凯,史琦隆,赵璐璐,等.面向动态扩散污染源的多无人机协同寻源与边界测绘[J/OL].机器人,1-15[2026-07-22].https://doi.org/10.13973/j.cnki.robot.250369.

链接

https://kns.cnki.net/kcms2/article/abstract?v=sFGZ-GfRoEUxpoqqH6aCDFL6B3XVDDtJsUla6H-nZa7NWZp6eaI226KnTPKPjbAMIU81-TWcGpk4nj95Z3SVmtIq7q4aMCRxj5xazOYzO6qr743MjNVKLrAQv3CYi5liayzXeKJAi_VLPD2DSJpb9ci7P9kBbYxtrLk57uIlLhOnwoul0pd_5g==&uniplatform=NZKPT&language=CHS

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IX. Parallel Robot

A Real-Time Human Pose Measurement System for Human-In-The-Loop Dynamic Simulators

Keywords

Human-In-The-Loop dynamic simulators, PKM active control, vision-based measurement system, 3D human pose estimation, YOLOv8 pose, YOLOv9 pose, real-time, TensorRT.

Abstract

The possibility of achieving real-time evaluation of human pose enables the ability to control robotic platforms based on user's pose (or even on user's inertial properties) in Human-In-The-Loop simulators, for sports and rehabilitation as an example. This study presents a vision-based, marker-less measurement system for real-time 3D human pose estimation. The system exploits pre-trained 2D human pose detection models and integrates an α-β-γ filter to reduce fluctuations in detected key points. It also introduces a novel Weighted Direct Linear Triangulation method, enhancing 3D reconstruction accuracy by assigning higher weights to key points consistent across current and previous frames. The method's accuracy and execution time are assessed using the public Human3.6M dataset, evaluating different model configurations, formats, camera setups, and acquisition modes for real-time applications. The YOLOv8x-pose model with four cameras achieves the highest accuracy, with a Mean-Per-Joint Position Error of 18.2 mm and an execution time of 15 ms, outperforming state-of-the-art methods. Converting models to the TensorRT framework reduces execution time by 4.2 ms without significant accuracy loss. The system is integrated into a clinical rehabilitation device, a three-degree-of-freedom parallel kinematic machine, to facilitate patient participation in exergames. The proposed human-pose estimation method achieves real-time performance, enabling the motion platform to be controlled dynamically based on the patient's actual standing pose.

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How NOKOV Contributes to the Research

In 2024, Sheng et al. [34] present a marker-less 3D HPE system using binocular stereo vision and OpenPose 2D HPE algorithm. It achieves a frame rate of 26 fps and demonstrates superior accuracy compared to NOKOV and Microsoft Kinect systems. However, limitations include the relatively low frame rate, sensitivity to environmental conditions, and issues with occlusions.

Citation Giulietti N, Todesca D, Carnevale M, et al. A Real-Time Human Pose Measurement System for Human-In-The-Loop Dynamic Simulators[J]. IEEE Access, 2025.

Link https://ieeexplore.ieee.org/document/10870253

A Spatial Variable-Structure Cable-Driven Parallel Robot Through Cables Wrapping Over a Convex Polyhedron

Keywords

cable-driven parallel robots, spatial variable-structure, complex environment, workspace expansion, inverse kinematics, control of mechanical systems

Abstract

The workspace of a cable-driven parallel robot (CDPR) in a complex environment is limited by obstacles and objects. To adapt a CDPR to a complex environment and enlarge the limited workspace, this article proposes a spatial variable-structure CDPR allowing cables to wrap over a convex polyhedron. A convex polyhedron can contain an obstacle or object approximately and guide cables to bypass the obstacle and object. This article investigates whether a cable wrapping over a convex polyhedron gets stuck by the edges from a statics perspective. An analytical approach to solving the path of a cable wrapping over a given sequence of edges is proposed. The concept of sequence-invariant space is proposed and an approach is developed based on the sequence-invariant space to track the wrapping edge sequence of a cable. Based on solving the path of cables, the inverse kinematics and statics of a spatial variable-structure CDPR are solved. An open-loop inverse kinematics-based control strategy is proposed for spatial variable-structure CDPRs. With the control strategy, the effectiveness of the proposed approaches in solving the path and tracking the wrapping edge sequence of a cable and in controlling a spatial variable-structure CDPR is verified, based on a CDPR prototype.

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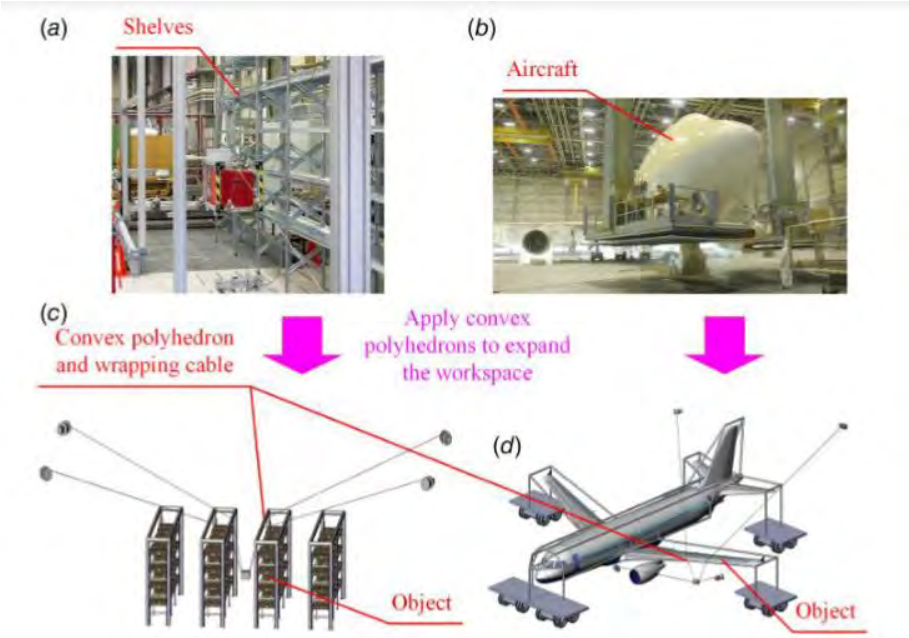

Fig. 1 CDPRs developed for (a) warehousing [22], (b) aircraft maintenance [23], and potential applications of CDPRs to (c) warehousing with a workspace expanded by allowing cables to wrap over convex polyhedrons and (d) aircraft maintenance with a workspace expanded by allowing cables to wrap over convex polyhedrons

How NOKOV Contributes to the Research

7.1 Prototype. A suspended CDPR prototype with threetranslational DOFs and four cables is developed and fixed to a plat-form, as shown in Fig. 18. A house-like convex polyhedron estab-lished by steel sticks with a diameter of 0.003 m is fixed to theplatform. The end-effector is driven by four servo motors (NiMo-tion; Nanjing, Jiangsu, China) via four separate cables. A suctioncup is fixed to the end-effector for manipulation tasks. The positionof the end-effector is defned in the base frame, denoted as Fh. Theorigin of the base frame is set to the center of the upper surface ofthe platform, as shown in Fig. 18. The position of anchor points inthe base frame is presented in Table I. The position of the verticesof the convex polyhedron in the base frame, denoted as V(i=1,2,...,9),is listed in Table 2. The position of theend-effector of a CDPR prototype is measured by a MotionCapture System (NoKov; Beijing, China) with a positioning accu-racy of 0.0002 m. A Raspberry Pi 4B (Raspberry Pi; Cambridge.United Kingdom)is utilized to implement the proposed

Citation Xiong H, Xu Y, Li Q, et al. A Spatial Variable-Structure Cable-Driven Parallel Robot Through Cables Wrapping Over a Convex Polyhedron[J]. Journal of Mechanisms and Robotics, 2026, 18(1): 011007.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001654323500002

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Cable Path Analysis and Kinematic Control of a Cable-Driven Parallel Robot Allowing Cables to Wrap on Cylinders or Spheres

Keywords

cable-driven parallel robots, cylinder, sphere, wrapping phenomenon, kinematics, and control of mechanical systems, theoretical and computational kinematics

Abstract

Scholars have proposed to allow cables to wrap on the base, the end-effector, or obstacles to expand the workspace of a cable-driven parallel robot (CDPR) in recent years. However, it is not entirely clear whether the path of a cable wrapped on the surface of different rigid bodies can or cannot be solved analytically. To this end, this paper analyzes the statics of a cable wrapped on a general surface and proposes necessary conditions for a path of a cable wrapped on a general frictionless surface. This paper shows that only the path of a cable wrapped on a frictionless surface included in a handful of surfaces, including cylinders and spheres, can be solved analytically. Then, the cable path and inverse velocity kinematics of a CDPR with cables, every of which wraps on a frictionless cylinder or a frictionless sphere, are solved. A CDPR demonstrator with cables wrapped on cylinders fixed to the base and a CDPR demonstrator with cables wrapped on a spherical end-effector are established. The kinematics-based control of the CDPR demonstrators is achieved.

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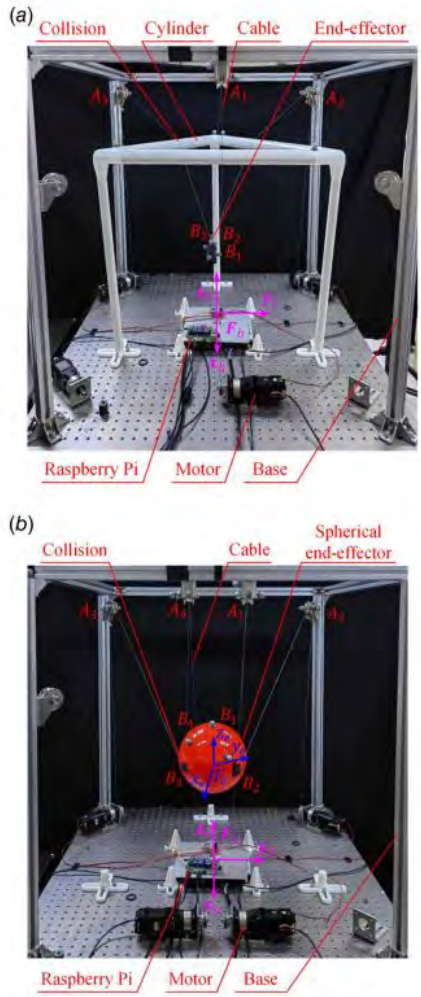

Fig. 1 CDPRs with cables wrapped on (a) cylindrical obstacles and (b) a spherical end-effector

How NOKOV Contributes to the Research

The end-effector is driven by four servo motors (NiMotion;Nanjing, Jiangsu, China) via four separate cables. The position and orientation of the end-effector are measured by a Motion Capture System (NoKov; Beijing, China). A Raspberry Pi 4B(Raspberry Pi; Cambridge, UK) is utilized to implement the control strategy.

Citation Xiong H, Xu Y, Yu Y, et al. Cable path analysis and kinematic control of a cable-driven parallel robot allowing cables to wrap on cylinders or spheres[J]. Journal of Mechanisms and Robotics, 2025, 17(1): 010903.

Link
https://asmedigitalcollection.asme.org/mechanismsrobotics/article/17/1/010903/1198173/Cable-Path-Analysis-and-Kinematic-Control-of-a?searchresult=1

Data-Driven Dynamics Modeling and Control Strategy for a Planar n -DOF Cable-Driven Parallel Robot Driven by n+1 Cables Allowing Collisions

Keywords

cable-driven parallel robot, collisions allowed, data-driven, dynamics-based control, cable-driven mechanisms

Abstract

Scholars have proposed to allow collisions of cables with the base, the end-effector, or obstacles to expand the workspace of cable-driven parallel robots (CDPRs) in recent years. However, allowing collisions also leads to new challenges in kinematics and dynamics modeling for CDPRs. To this end, this article focuses on a planar fully constrained n-degree-of-freedom (DOF) CDPR driven by n + 1 cables allowing collisions and develops a data-driven dynamics modeling strategy. The data-driven dynamics modeling strategy can address the collisions and optimal tension distribution issues simultaneously. Based on the data-driven dynamics modeling strategy, this article proposes a data-driven dynamics-based control strategy for the planar CDPR allowing collisions. A planar two-DOF CDPR prototype driven by three cables is established to evaluate the data-driven dynamics modeling strategy and data-driven dynamics-based control strategy.

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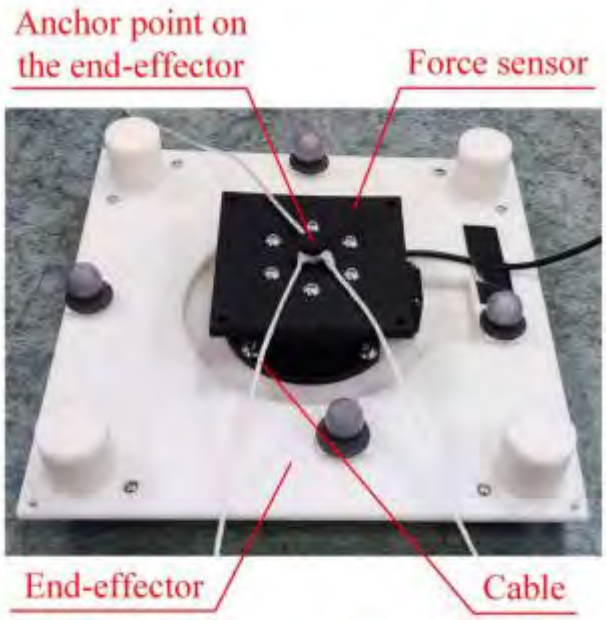

Fig. 7 Force sensor fixed to the end-effector

How NOKOV Contributes to the Research

The feasible cable tension ranges from 0 N to 45 N. The three cables are connected to the same anchor point fixed to a force sensor (Hypersen Technologies Co., Ltd, Shenzhen, Guangdong, China), as shown in Fig. 7. The resultant force applied on the end-effector by cables is measured by the force sensor. The position and the velocity of the end-effector are measured by a motion capture system (Nokov Co., Ltd., Beijing, China). The mass of the end-effector is 4.772 kg. The operation frequency of the CDPR prototype is 50 Hz.

Citation Xu, G., Zhu, H., Xiong, H., and Lou, Y. (July 20, 2023). "Data-Driven Dynamics Modeling and Control Strategy for a Planar n-DOF Cable-Driven Parallel Robot Driven by n + 1 Cables Allowing Collisions." ASME. J. Mechanisms Robotics. May 2024; 16(5): 051008.

Link
https://asmedigitalcollection.asme.org/mechanismsrobotics/article/16/5/051008/1164091/Data-Driven-Dynamics-Modeling-and-Control-Strategy?searchresult=1

Design and analysis of a concentrated-driven bionic-leg capable of omnidirectional legged locomotion based on 3-Dimensional dual-parallelogram-linkages

Keywords

3-Dimensional dual-parallelogram-linkages, bionic leg, omnidirectional legged locomotion, concentrated-driven, kinematics model

Abstract

The Flexible, fast and lightweight leg mechanism is the key to improve legged robot's mobility, efficiency and adaptability on complex terrain. Inspired by the motion mechanism of legged animals, we report a concentrated-driven omnidirectional legged locomotion bionic leg – OmniLeg. All the motor actuators are centrally installed in the hip plate of the proposed leg to reduce the rotational inertia. Meanwhile, the special 3-Dimensional dual-parallelogram-linkages transmission mechanism enables it to have the ability of omnidirectional legged locomotion in 3-Dimensional space and makes the posture of leg's endpoint does not change with the motion of the leg mechanism which simplifying the motion control. In this paper, firstly the theoretical model, including mobility, kinematics model, inverse kinematics model, dimension parameters and workspace model, have been derived, analyzed and verified with the design and control of the real prototype. Next, to demonstrate the ability of omnidirectional legged locomotion intuitively, we manufacture a single-legged omnidirectional mobile robot and design a quadruped robot, and the simulation and experiment result illustrate that the design and analytical mode of OmniLeg is feasible and correct, which could be widely applied in the field of legged robot.

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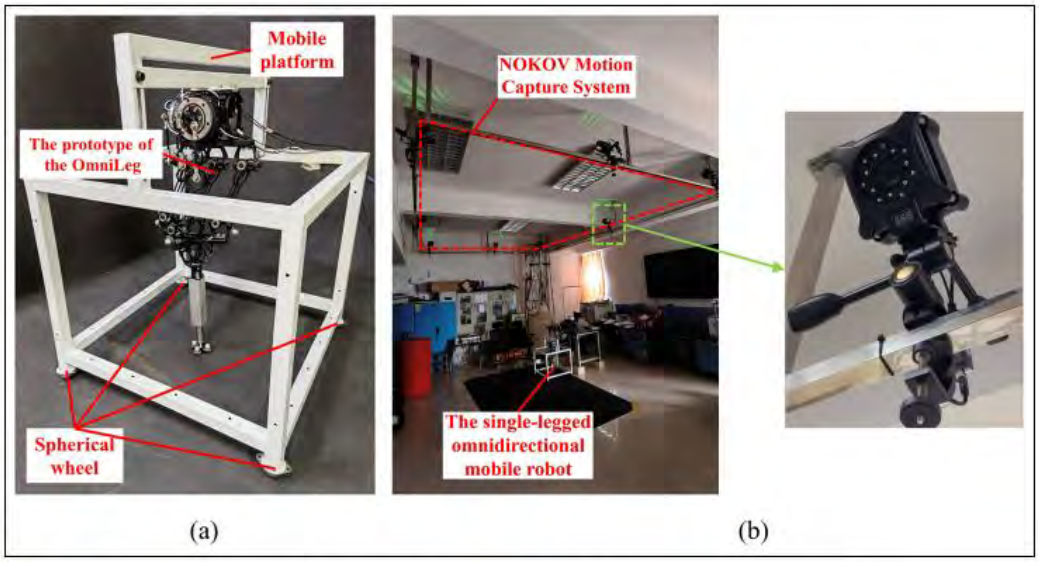

Figure 13. (a) The single-legged omnidirectional mobile robot and (b) the experiment of motion capture.

How NOKOV Contributes to the Research

The motionof the single-legged omnidirectional mobile robot wascaptured by NOKOV Motion Capture System pro-duced by Beijing Nokov Science and Technology Co.,Ltd. The type of the camera of this system is MARS 2H.

Citation Xu Y, Luo Z, Shang J, et al. Design and analysis of a concentrated-driven bionic-leg capable of omnidirectional legged locomotion based on 3-Dimensional dual-parallelogram-linkages[J]. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2024, 238(2): 459-478.

Link https://journals.sagepub.com/doi/abs/10.1177/09544062231167022

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Design and Development of a New Cable-Driven Parallel Robot for Waist Rehabilitation

Keywords

Mechanics analysis, prototype design, rehabilitation training experiment, two-level controller, waist rehabilitation

Abstract

This paper proposes a cable-driven parallel waist rehabilitation robot with two-level control algorithm to assist the patients with waist injuries to do some rehabilitation training. The uniqueness of the robot is that it can accurately implement the relative lateral bending, flexion, extension, and rotation of the waist on the premise of the safety. This is enabled by a mechanism design according to the motion characteristics of the human waist, and it can satisfy the need of different waist injury patients. The kinematics and dynamics of the robot are analyzed. In addition, a two-level controller is introduced to improve the accuracy of the rehabilitation training trajectory on the premise of the safety of patients and reduce the system calculation. The proportion-integration-differentiation (PID) algorithm is adopted to realize the position control in the low-level controller to ensure the accuracy of the robot. In the high-level controller, the fuzzy algorithm is used to adjust the parameters of the low-level controller according to the tension variation of cables, which ensures the patient safety and the stable operation of the robot. Finally, a prototype waist rehabilitation robot is developed for experimental calibration and performance testing. Results indicate that the designed robot system can achieve the waist rehabilitation training and the control algorithm can improve the system performance under the external disturbance.

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Fig. 7 The system of the waist rehabilitation robot prototype

How NOKOV Contributes to the Research

The cable-driven parallel waist rehabilitation robot prototype under study including the cable-driven parallel motion platform, the fixing device of the upper limb and sensor system is shown in Fig. 7. Eight visible-range stereo cameras (Mars8H, Nokov) were used to measure the movement of the platform with sub-milimeter precision, a position sensor (MPS-S-1000, Chino) with 0.02 mm resolution for length measurement, and a tension sensor (ZNLBM-50, Chino) to measure the cable force.

Citation Chen Q, Zi B, Sun Z, et al. Design and development of a new cable-driven parallel robot for waist rehabilitation[J]. IEEE/ASME transactions on mechatronics, 2019, 24(4): 1497-1507.

Link https://ieeexplore.ieee.org/abstract/document/8716563/

Design and Experiment of a Compact 3-DOF Humanoid Wrist with High Payload Capacity

Keywords

Humanoid robots · Humanoid wrist · Bionic design · 3-DoF

Abstract

The wrist unit is crucial in humanoid robots, determining their operational dexterity and precision. To address current challenges such as excessive size, limited Degrees of Freedom (DoFs), and insufficient load capacity, we propose a 3-DoF humanoid wrist inspired by the human forearm and wrist anatomy. This paper explores the principles of wrist bionic design and introduces a parallel mechanism actuated by a brushless DC motor (BLDC)-ball screw to achieve flexion/extension (F/E) and radial flexion/ulnar deviation (R/U), as along with pronation/supination (P/S) through an end-coupling design. We conducted an analysis on the inverse kinematic model and singularities of the humanoid wrist. Additionally, the workspace and motion capabilities of the humanoid wrist were evaluated. A prototype based on this design was built to demonstrate its motion and functional performance, verifying the feasibility and practicality of the humanoid wrist. This research provides a more compact design approach for future humanoid wrist development.

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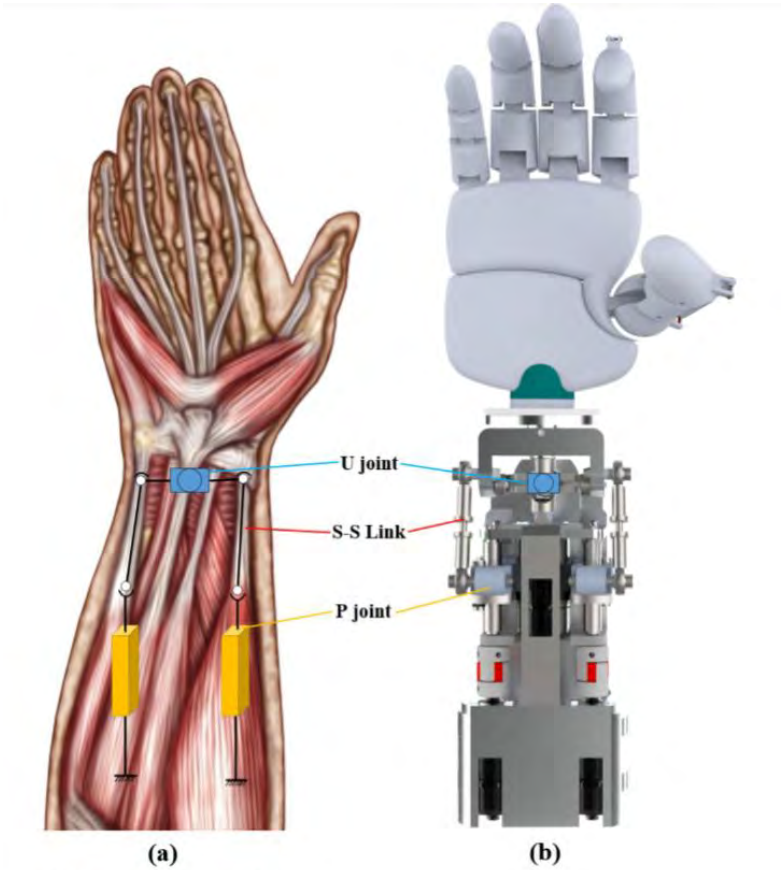

Fig. 1 a Anatomical structural equivalence. b 3-Dimensional model

How NOKOV Contributes to the Research

4.2 Motion Performance Experiments
In this section, to evaluate the feasibility and motion capabilities of the prototype, we built a testbed, see Fig. 11a. The trajectory of the prototype's end is monitored by Nokov motion capture system with ±0.15 mm accuracy, which is produced by Beijing Nokov Science and Technology Co., Ltd. The eight cameras of this system are mounted on a steel truss with a length, width, and height of 4.8 × 3.6 × 3 m. The experimental data are collected by the Seeker software accompanying the system. Motion pictures are captured and saved by a high-speed camera (GoPro) in experiments.

Citation Wang S, Luo Z, Chen S, et al. Design and Experiment of a Compact 3-DOF Humanoid Wrist with High Payload Capacity[J]. Journal of Bionic Engineering, 2025, 22(3): 1265-1286.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001458510000001

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Design and Experiments of a Human-Leg-Inspired Omnidirectional Robotic Leg

Keywords

Human leg, Robotic leg, Omnidirectional legged locomotion, Spatial dual-parallelogram-linkages, Spatial closed-loop four-bar

Abstract

Bionic-based robotic legs enable the legged robots with elegant and agile mobility in multi-terrain environment, just like natural living beings. And the smart design could efficiently improve the performance of a robotic leg. Inspired by the simplified human leg structure, we present a 3-DOF robotic leg—OmniLeg, that is capable of making omnidirectional legged locomotion while keeping constant posture of the foot. Additionally, the concentrated drive mode, in which all the motor actuators are installed in the torso and do not move with the leg, minimizes the inertia of the robotic leg. In this paper, the modular design, the kinematics model, the structural analysis, the workspace, and the performance evaluation of the OmniLeg are discussed. Furthermore, we build a prototype based on the proposed design, and the precision of it is verified by the error calibration experiment which is conducted by tracking the trajectory of the prototype's endpoint. Then, we present an OmniLeg-based single legged mobile robot. The capability of omnidirectional legged locomotion of the OmniLeg is demonstrated by the experiments.

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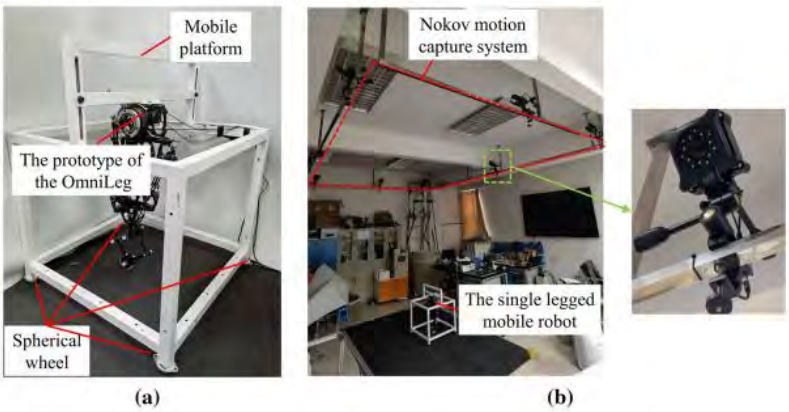

Fig. 14 **a** The single legged mobile robot. **b** The experimental equipment and experimental site

How NOKOV Contributes to the Research

The experimental equipment is the Nokov motion capture system with±0.15 mm accuracy, which produced by Beijing Nokov Science and Technology Co., Ltd.
The motion state of the robot is also monitored by Nokov motion capture system.
The experimental site is a rubber paving fooring with a length and width of 3×2 m, which reducing the probability of slippage between the foot and the ground, see Fig. 14b.

Citation Xu Y, Luo Z, Bai X, et al. Design and experiments of a human-leg-inspired omnidirectional robotic leg[J]. Journal of Bionic Engineering, 2023, 20(6): 2570-2589.

Link https://link.springer.com/article/10.1007/s42235-023-00412-3

Design and Optimization of a Cable-Driven Parallel Polishing Robot With Kinematic Error Modeling

Keywords

cable-driven parallel robot, mechanical design, kinematic error modeling, multiobjective optimization, uncertainty analysis

Abstract

This article presents the design and optimization of a cable-driven parallel polishing robot (CDPPR) with kinematic error modeling and introduces an improved nondominated sorting genetic algorithm II (NSGA-II) for multiobjective optimization. First, the mechanical design and kinematic and static modeling of the CDPPR are conducted. Subsequently, a kinematic error transfer model is established based on the evidence theory by considering the change of exit points of cables, and an error index is derived to measure the accuracy of the robot. Besides, another two performance indices including the workspace and static stiffness are proposed. Thus, a multiobjective optimization model is established to optimize the workspace, static stiffness, and error index, and an improved NSGA-II is developed. Finally, an experimental scaled prototype of the CDPPR is constructed, and numerical examples and experimental results demonstrate the effectiveness of the improved NSGA-II and the stability of the optimal configuration.

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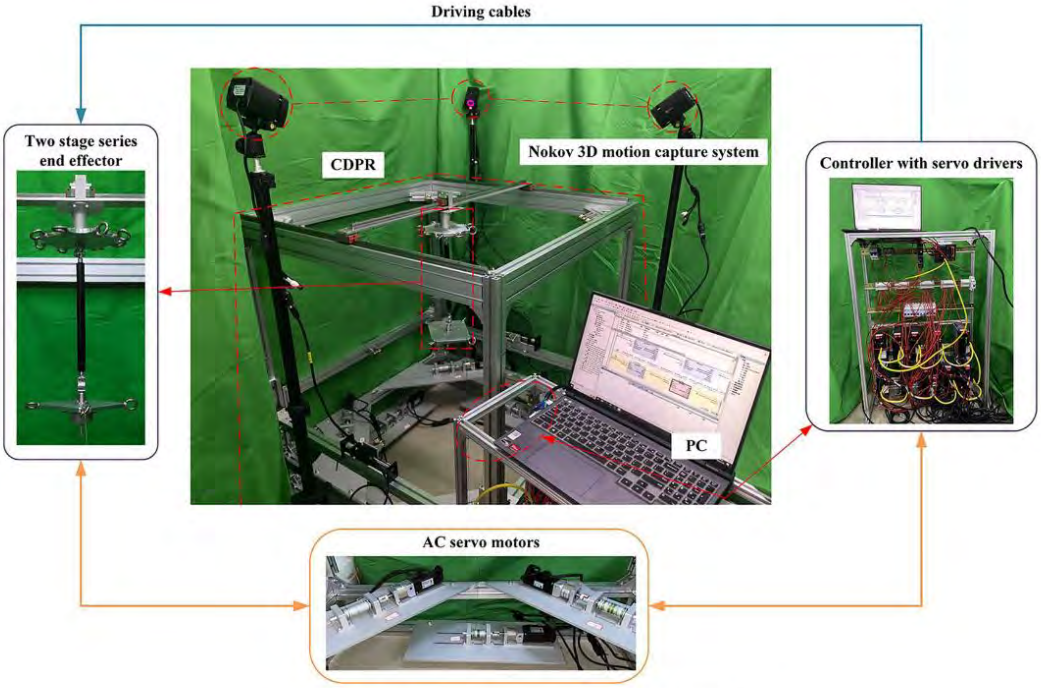

Fig. 16 Experimental model prototype of CDPPR

How NOKOV Contributes to the Research

The material of the cable is ultra-high molecular weight polyethylene, which has the advantages oflightweight, high strength, high Young's modulus, and low shrink-age. The trajectory of the EE is measured by a Nokov optical 3Dmotion capture system. The system consists of three cameras foroptical tracking in six degrees of freedom.

Citation Zhou B, Wu S, Zi B, et al. Design and optimization of a cable-driven parallel polishing robot with kinematic error modeling[J]. Journal of Mechanical Design, 2025, 147(1): 013304.

Link
https://asmedigitalcollection.asme.org/mechanicaldesign/article/147/1/013304/1201405/Design-and-Optimization-of-a-Cable-Driven-Parallel?searchresult=1

Design and Validation of a Brain-Controlled Hip Exoskeleton for Assisted Gait Rehabilitation Training

Keywords

gait rehabilitation; brain-controlled; hip exoskeleton; kinematic redundancy; augmented reality and visual stimulation (AR-VS) paradigm; hybrid control

Abstract

This study presents an integrated micro-system solution to address the challenges of gait instability in patients with impaired hip motor function. We developed a novel wearable hip exoskeleton, where a flexible support unit and a parallel drive mechanism achieve self-alignment with the biological hip joint to minimize parasitic forces. The system is driven by an active brain–computer interface (BCI) that synergizes an augmented reality visual stimulation (AR-VS) paradigm for enhanced motor intent recognition with a high-performance decoding algorithm, all implemented on a real-time embedded processor. This integration of micro-sensors, control algorithms, and actuation enables the establishment of a gait phase-dependent hybrid controller that optimizes assistance. Online experiments demonstrated that the system assisted subjects in completing 10 gait cycles with an average task time of 37.94 s, a correlated instantaneous rate of 0.0428, and an effective output ratio of 82.17%. Compared to traditional models, the system achieved an 18.64% reduction in task time, a 28.31% decrease in instantaneous rate, and a 7.36% improvement in output ratio. This work demonstrates a significant advancement in intelligent micro-system platforms for human-centric rehabilitation robotics.

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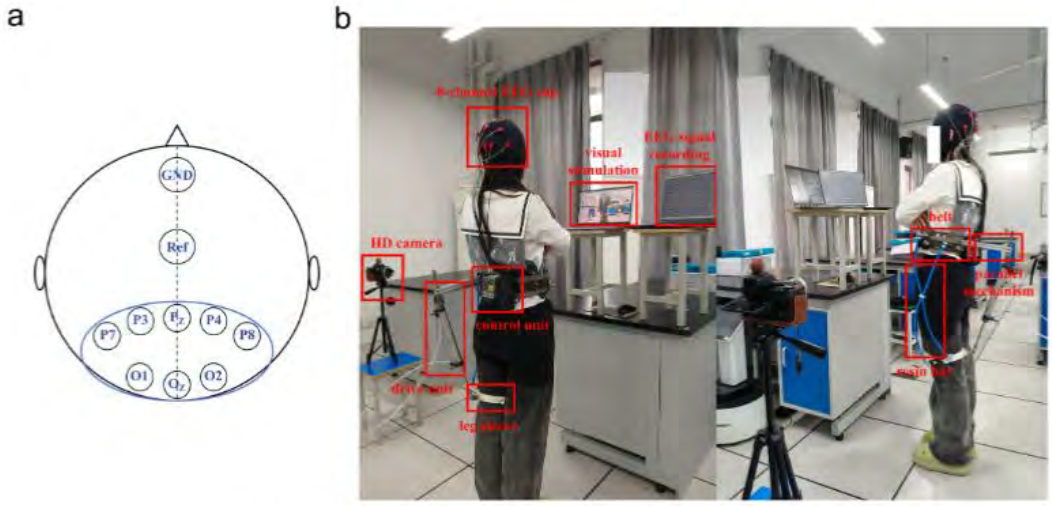

Figure 13. Experimental equipment. **(a)** Acquisition of EEG signals. **(b)** Experimental setup.

How NOKOV Contributes to the Research

The biological hip joint center (Ap) was determined from the hip marker trajectories using a NOKOV Mars 4H motion capture system. The system, comprising 10 high-speed infrared cameras (1280 × 1024 pixels, 100 Hz), achieved a dynamic measurement accuracy of better than 1.0 mm. Therefore, the inter-articular misalignment d for any movement of the subject's hip in the sagittal and coronal axis directions can be calculated, and the results are shown in Figure 6, with the red circle showing that the subject is in a normal walking state. The mean value of the maximum misalignment dmax at this point in the subject's normal walking state (hip swing range is −22° to 32°) was 32.4 mm; at the maximum swing joint angle of 54°, dmax was 55.9 mm.

Citation Wang C, Cheng B, Tang Q, et al. Design and Validation of a Brain-Controlled Hip Exoskeleton for Assisted Gait Rehabilitation Training[J]. Micromachines, 2025, 16(12): 1364.

Link https://www.mdpi.com/2072-666X/16/12/1364

Dynamic Obstacle Avoidance for Cable-Driven Parallel Robots With Mobile Bases via Sim-to-Real Reinforcement Learning

Keywords

Collision avoidance, machine learning for robot control, parallel robots, wire mechanism

Abstract

A Cable-Driven Parallel Robot (CDPR) with Mobile Bases (MBs) can modify its geometric architecture and is suitable for manipulation tasks in constrained environments. In manipulation tasks, a CDPR with MBs inevitably encounters obstacles, including dynamic obstacles. However, the high dimensional state space and a considerable number of constraints caused by multiple cables and MBs make the real-time dynamic obstacle avoidance of a CDPR with MBs challenging. This letter proposes a Reinforcement Learning (RL)-based dynamic obstacle avoidance method for a CDPR with MBs to deal with dynamic obstacles in real time. To explain the RL-based dynamic obstacle avoidance method, this letter focuses on a CDPR with four fixed-length cables connected to four MBs. An RL-based Obstacle Avoidance Controller (OAC) is developed and integrated into a trajectory tracking controller to address the dynamic obstacle avoidance problem of a CDPR with MBs tracking a target trajectory. To explain and evaluate the RL-based dynamic obstacle avoidance method further, an RL-based OAC is trained in a Mujoco simulator and transferred to a CDPR with four fixed-length cables connected to four MBs in the real world.

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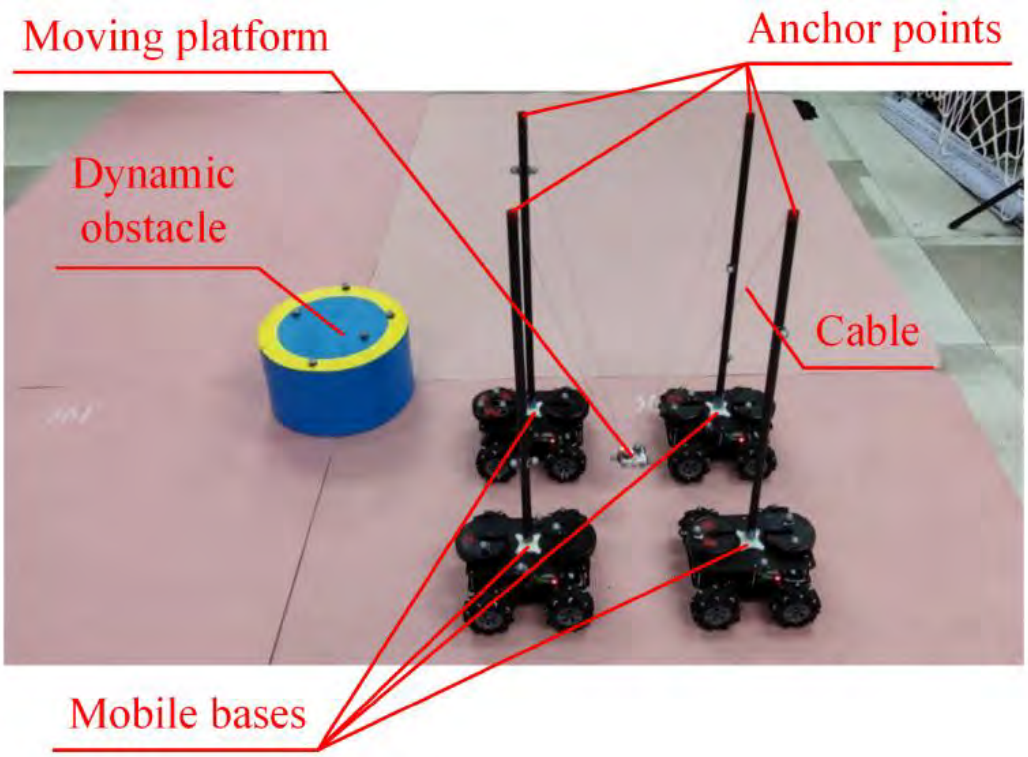

Fig. 1. A CDPR with four mobile bases.

How NOKOV Contributes to the Research

In experiments, the position of the MP, the position of MBs, and the position and shape of a dynamic obstacle are observed based on a NOKOV motion capture system.

Citation Y. Liu, Z. Cao, H. Xiong, J. Du, H. Cao and L. Zhang, "Dynamic Obstacle Avoidance for Cable-Driven Parallel Robots With Mobile Bases via Sim-to-Real Reinforcement Learning," in IEEE Robotics and Automation Letters, vol. 8, no. 3, pp. 1683-1690, March 2023, doi: 10.1109/LRA.2023.3241801.

Link https://ieeexplore.ieee.org/document/10035491

Fuzzy Adaptive Whale Optimization Control Algorithm for Trajectory Tracking of a Cable-Driven Parallel Robot

Keywords

Cable-driven parallel robot, fuzzy control, particle swarm optimization algorithm, trajectory tracking, whale optimization algorithm

Abstract

This paper proposes a fuzzy proportion integration differentiation (PID) control strategy based on an adaptive whale optimization algorithm (FPID-AWOA) for trajectory tracking of a cable-driven parallel robot (CDPR). A mechanical prototype, and kinematic and dynamic models of the CDPR are established. Thus, new fuzzy rules are developed and a new fuzzy PID controller is designed. Subsequently, the AWOA is introduced to optimize quantization and scale factors of the fuzzy PID controller to obtain the optimal solution. Among them, AWOA is an improvement on WOA. Numerical examples show that the fuzzy PID control strategy based on adaptive whale optimization algorithm (FPID-AWOA) has higher CDPR trajectory tracking accuracy than the traditional fuzzy PID control strategy, the fuzzy PID control strategy based on whale optimization algorithm (FPID-WOA), and the fuzzy PID control strategy based on particle swarm optimization (FPID-PSOA). In comparison with the FPID and FPID-PSOA, the experimental results show that the trajectory tracking error of the proposed FPID-AWOA is reduced by 51.2% and 19.5% in the X -axis direction, respectively, 64.2% and 49.7% in the Y -axis direction, respectively, and 29.1% and 12.2% in the Z -axis direction, respectively. Note to Practitioners — The motivation of this article stems from the need to develop efficient trajectory tracking control algorithms for practical applications of CDPRs. Fuzzy PID control is widely used in CDPRs because of its good robustness and fast response speed. However, the fuzzy parameter selection depends on experience, and the efficiency is low. In order to obtain high quality quantization and scale factors quickly, we propose FPID-AWOA. It uses AWOA to find the optimal quantization and scale factors, which makes the fuzzy PID control get better performance. FPID-AWOA can also be applied to control other robots. In future research, we will extend the proposed approach to multiple CDPRs working collaboratively as well as to mobile operational requirements.

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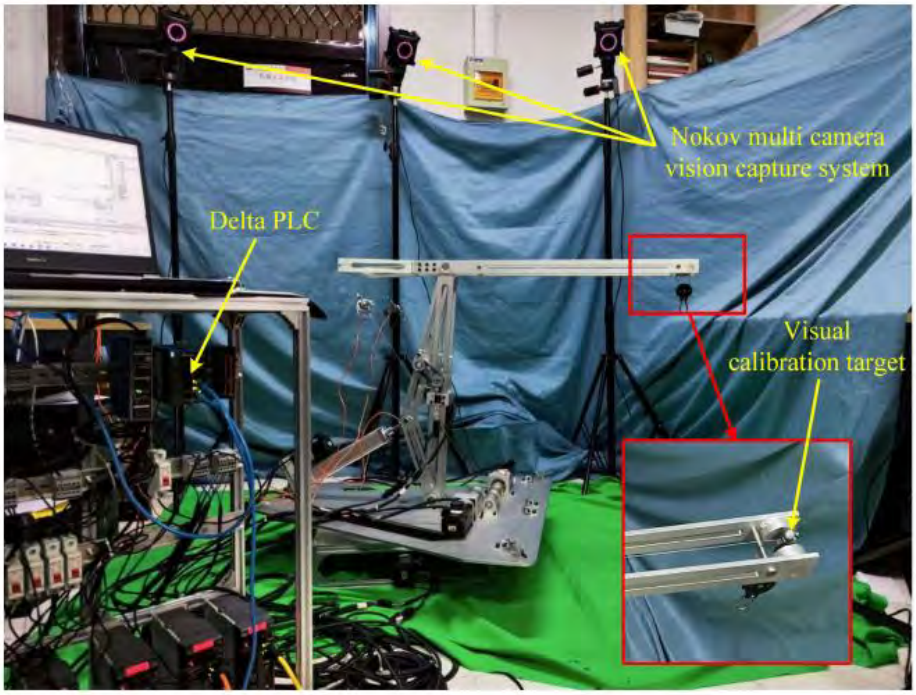

Fig. 13. The control experiment platform.

How NOKOV Contributes to the Research

In order to verify the effectiveness of the control algorithm proposed in this paper, a control experiment platform of the CDPR is built. The control experiment platform is shown in Fig.13. The CDPR is controlled by Delta PLC. The control program is written by Delta software. The trajectory of the CDPR is captured by the Nokov multi-camera visual capture system. The trajectory of the visual calibration tar-get acquired by the camera is the end motion track of the CDPR.

Citation Zhou B, Wang Y, Zi B, et al. Fuzzy adaptive whale optimization control algorithm for trajectory tracking of a cable-driven parallel robot[J]. IEEE Transactions on Automation Science and Engineering, 2023.

Link https://ieeexplore.ieee.org/abstract/document/10267913

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Kinematic Calibration of a Cable-Driven Parallel Robot for 3D Printing

Keywords

cable-driven parallel robot, kinematic calibration, error analysis, additive manufacturing

Abstract

Three-dimensional (3D) printing technology has been greatly developed in the last decade and gradually applied in the construction, medical, and manufacturing industries. However, limited workspace and accuracy restrict the development of 3D printing technology. Due to the extension range and flexibility of cables, cable-driven parallel robots can be applied in challenging tasks that require motion with large reachable workspace and better flexibility. In this paper, a cable-driven parallel robot for 3D Printing is developed to obtain larger workspace rather than traditional 3D printing devices. A kinematic calibration method is proposed based on cable length residuals. On the basis of the kinematic model of the cable-driven parallel robot for 3D Printing, the mapping model is established among geometric structure errors, zero errors of the cable length, and end-effector position errors. In order to improve the efficiency of calibration measurement, an optimal scheme for measurement positions is proposed. The accuracy and efficiency of the kinematics calibration method are verified through numerical simulation. The calibration experiment based on the motion capture system indicates that the position error of end-effector is decreased to 0.6157 mm after calibration. In addition, the proposed calibration method is effective and verified for measurement positions outside optimal positions set through experiments.

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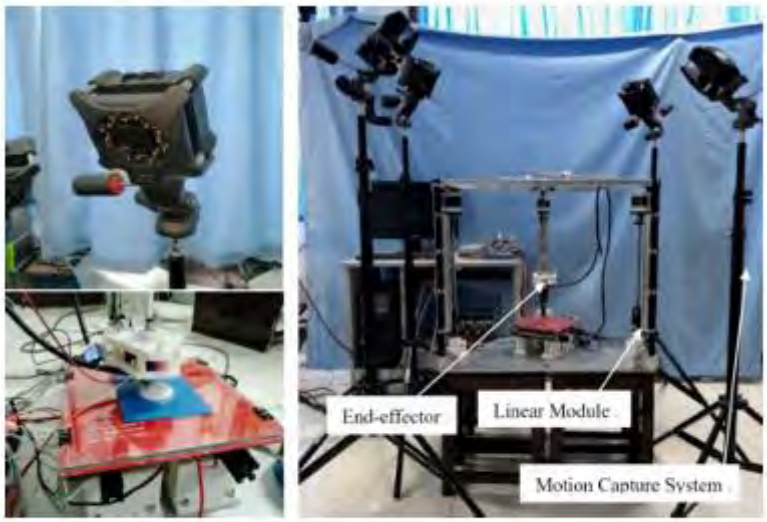

Figure 9. Experimental device of kinematic calibration.

How NOKOV Contributes to the Research

The experimental platform of the CDPR for 3D printing is shown in Figure 9, the stepping motordrives the linear module to drive the fixed-length cables to realize the movement of the end-effector.Therefore, the displacements of the sliders on the linear module is equal to the change of cable length.The coordinates of the markers attached to the sliders can be measured with the motion capture system.

Citation Qian S, Bao K, Zi B, et al. Kinematic calibration of a cable-driven parallel robot for 3D printing[J]. Sensors, 2018, 18(9): 2898.

Link https://www.mdpi.com/1424-8220/18/9/2898

Kinematics optimization of a novel 7-DOF redundant manipulator

Keywords

Kinematics analysis, Spherical parallel mechanism, Redundant manipulator, LDWPSO

Abstract

Redundant manipulators can accomplish complex tasks due to the redundant degree of freedom (DOF). At the same time, their kinematics calculations are complicated. In this study, the kinematics solution for a self-designed 7-DOF redundant anthropomorphic manipulator is obtained, and an optimization method is provided to optimize the motion time of the manipulator in the same trajectory. Kinematics analysis of the spherical parallel shoulder joint was performed by using a geometric method and coordinate transformation. Kinematics analysis of the redundant manipulator was performed by a geometric method with an optimizing arm angle. Linearly decreasing weight particle swarm optimization (LDWPSO) was used to optimize the arm angle to minimize the motion time of the manipulator. The kinematics calculation of the shoulder joint was verified by a combination of SOLIDWORKSTM and MATLABTM software. The kinematics calculation of the redundant manipulator was verified by MATLABTM. The linear, circular and 8-shaped motion trajectories were used to evaluate the proposed method in the simulation. The simulation results showed that the motion time with optimization of the arm angle was only 16% – 30% of that without optimization. Furthermore, the proposed method was evaluated through real manipulator experiments, and the experimental results were similar to those in the simulation.

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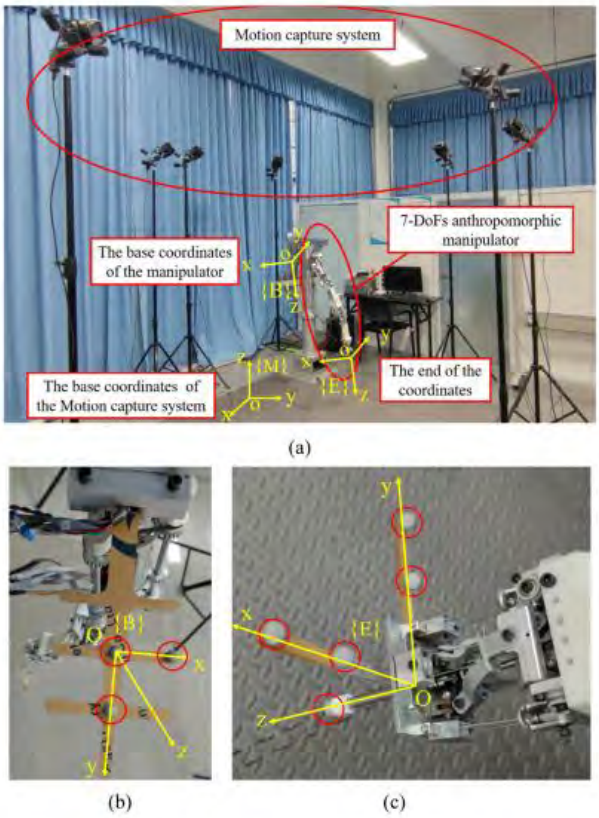

Fig. 22. Kinematics experiment on the manipulator.

How NOKOV Contributes to the Research

This section describes an experiment performed to test the kinematics of the whole arm. As shown in Fig. 22, the experimental platform is built, A motion capture system is used to evaluated the manipulator. The motion capture system is composed of eightMars1.3H infrared high-speed cameras of the NOKOV system,with a resolution of 2048 \ 1088 and an accuracy of 0.02 mm.

Citation Chen Y, Zhang X, Huang Y, et al. Kinematics optimization of a novel 7-DOF redundant manipulator[J]. Robotics and Autonomous Systems, 2023, 163: 104377.

Link https://www.sciencedirect.com/science/article/abs/pii/S0921889023000167

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Modeling and Experimental Validation of a Cable-Driven Robot for Three-Dimensional Printing Construction

Keywords

lunar 3D printing, cable-driven printer, fuzzy control, motion control

Abstract

Cable-driven robots are characterized by a large workspace, high speed, and load-to-weight ratio, providing a new technology approach for large-scale autonomous 3D construction of lunar surface shelters. A novel deployable cable-driven construction 3D printer (CDCP) is developed in this study. Guiding pulleys are considered and modeled to improve the accuracy of the system. A fuzzy adaptive differential evolution PID (FDEPID) control is proposed to reduce end-effector motion errors in Cartesian space and thus improve printing quality and stability. Concentric and zigzag infill strategies are compared to optimize printing efficiency and infill effectiveness in path planning. The simulations focus on evaluating the effects of pulley kinematics on trajectory tracking, evaluating system dynamics under low-gravity conditions, and examining the effectiveness of motion control and path planning methods. Finally, experiments are carried out to validate the proposed FDEPID control and path planning strategies which demonstrate the great potential of the developed cable-driven printer in the construction of lunar architecture.

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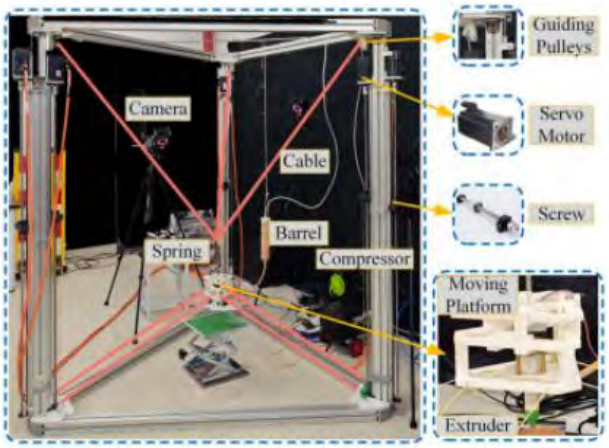

Fig. 11 Experimental platform of a CDCP

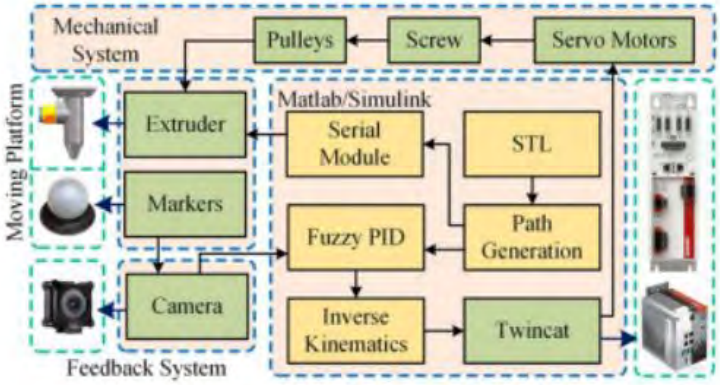

Fig. 12 Workflow diagram for a CDCP

How NOKOV Contributes to the Research

A Nokov multi-camera vision capture system records the CDCP trajectory. The captured trajectory of the vision calibration target represents the end-effector motion of the CDCP. The performance of the OLC, PID, and FDEPID control are compared for both concentric and zigzag infill patterns to demonstrate the effectiveness of the FDEPID control algorithm.

Citation Qian S, Li C, Zhao Z, et al. Modeling and Experimental Validation of a Cable-Driven Robot for Three-Dimensional Printing Construction[J]. Journal of Mechanisms and Robotics, 2025, 17(6): 061002.

Link
https://asmedigitalcollection.asme.org/mechanismsrobotics/article/17/6/061002/1207811/Modeling-and-Experimental-Validation-of-a-Cable?searchresult=1

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Motion Analysis and Orientation Holding Control of a 3-RRR Rigid-Flexible Coupling Mechanism for Photovoltaic Panel Assembly

Keywords

cable-driven robot, orientation holding control, kinematics, quasi-sliding mode control, simulation and experiment, photovoltaic (PV) panel assembly, design for manufacturing, design of experiments, parallel robots, robot design, robot kinematics,robotic

Abstract

This article is concerned with the design and control of a 3-Revolute-Revolute-Revolute Parallel Manipulator (3-RRR) rigid-flexible coupling mechanism, to meet the high flexibility and stability requirements for holding control in photovoltaic (PV) panel assembly. A mathematical model is established including forward, inverse, and differential kinematics, which is collapsed into the standard state-space equations. The relationship between the spherical workspace of a 3-RRR rigid-flexible coupling mechanism and the size of its orientation transformations is analyzed. Due to the orientation holding requirements in the PV panel assembly process, a quasi-sliding mode control (QSMC) is designed for orientation adjustment of the 3-RRR mechanism. The effectiveness of the algorithm is verified through simulation and experiment, compared with the traditional PID control. An industrial robot is connected with the 3-RRR rigid-flexible coupling mechanism and programmed to exert continuous disturbance and step signals. The motion capture cameras are adopted to capture the end orientation transformations in real time as feedback. Compared with the traditional PID control method, the mean absolute errors with QSMC are reduced by 64.55% and 65.54% in α and β orientations, respectively. The maximum convergence time in α and β orientations subject to the step signals is accelerated by 52.98% and 54.36%, respectively.

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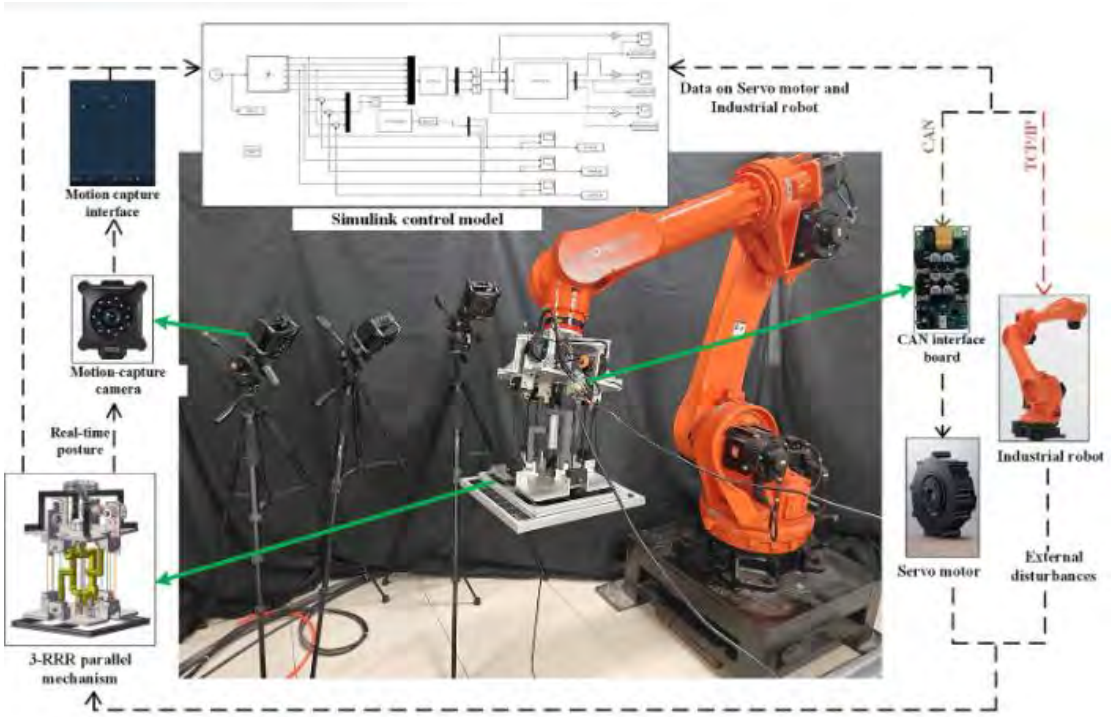

Fig. 11 Experimental scenarios and procedures

How NOKOV Contributes to the Research

The 3-RRR mechanism is driven by three servo motors andfixedto the end of the 65-kg industrial robot (YH1050A-230). Externaldisturbances are applied to the 3-RRR mechanism using the industrial robot, and the moving platform orientation is capturedin real time by a motion capture system (NOKOV M2HR1A8364). The control system is composed of a computer equipped with MATLAB/SIMULINK real-time control environmentand a CAN interface board. The camera data are transmitted to SIMULINK through TCP/IP for control of the industrial robot. Thecontrol algorithms are implemented in the computer. The CAN inter-face board is responsible for transferring signal variables between thecomputer and the 3-RRR mechanism. The motor data are transmitted to MATLAB/SIMULINK, realizing real-time control of the servo motor.

Citation Qian S, Song G, Zi B. Motion Analysis and Orientation Holding Control of a 3-RRR Rigid-Flexible Coupling Mechanism for Photovoltaic Panel Assembly[J]. Journal of Mechanical Design, 2025, 147(10): 103302.

Link
https://asmedigitalcollection.asme.org/mechanicaldesign/article/147/10/103302/1213239/Motion-Analysis-and-Orientation-Holding-Control-of?searchresult=1

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Motion Planning for a Cable-Driven Lower Limb Rehabilitation Robot with Movable Distal Anchor Points

Keywords

Bionic robot, Cable-driven parallel robot (CDPR), Lower limb rehabilitation robot, Movable anchor point, Motion planning, Simulation

Abstract

This article introduces a cable-driven lower limb rehabilitation robot with movable distal anchor points (M-CDLR). The traditional cable-driven parallel robots (CDPRs) control the moving platform by changing the length of cables, M-CDLR can also adjust the position of the distal anchor point when the moving platform moves. The M-CDLR this article proposed has gait and single-leg training modes, which correspond to the plane and space motion of the moving platform, respectively. After introducing the system structure configuration, the generalized kinematics and dynamics of M-CDLR are established. The fully constrained CDPRs can provide more stable rehabilitation training than the under-constrained one but requires more cables. Therefore, a motion planning method for the movable distal anchor point of M-CDLR is proposed to realize the theoretically fully constrained with fewer cables. Then the expected trajectory of the moving platform is obtained from the motion capture experiment, and the motion planning of M-CDLR under two training modes is simulated. The simulation results verify the effectiveness of the proposed motion planning method. This study serves as a basic theoretical study of the structure optimization and control strategy of M-CDLR.

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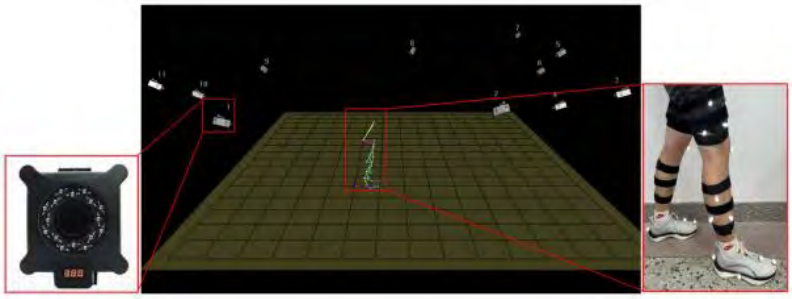

Fig. 7 Motion capture experiment set-up

How NOKOV Contributes to the Research

This study uses the Nokov motion capture system to collect lower limb motion data. As shown in Fig. 7, 11 motion capture cameras are used in the experiment. The experimenter has 2 markers on the shoulder, 3 markers at the waist, 3 markers for each thigh and shank, 1 marker for each knee and each ankle, 4 markers on each foot. The experimenter performs 5 s static standing, 10 s straight walking and 3 times right leg stretches.

Citation Li J, Wang K, Wang Y, et al. Motion planning for a cable-driven lower limb rehabilitation robot with movable distal anchor points[J]. Journal of Bionic Engineering, 2023, 20(4): 1585-1596.

Link https://link.springer.com/article/10.1007/s42235-023-00349-7

Online decentralized planning for a cable-driven parallel robot with aerial and ground actuators through multi-agent reinforcement learning

Keywords

cable-driven parallel robot, aerial actuators, decentralized planning, multi-agent reinforcement learning

Abstract

Scholars have proposed a cable-driven parallel robot (CDPR) with aerial and ground actuators, referred to as a cable-towed aerial platform (CTAP), to address the limited ability to withstand external forces of existing unmanned arrival vehicle (UAV)-based aerial platforms. To tackle practical problems (e.g., firefighting), a CTAP may need to perform motion planning in an environment with obstacles and communication failures. To this end, this article proposes an online decentralized planning approach based on multi-agent reinforcement learning (MARL) for a CTAP to achieve real-time motion planning in a communication-denied environment with obstacles. This article then defines the state and action spaces of a MARL-based planner. A reward function is designed for the MARL-based planning approach according to the widely used optimization-based planning approach. This study has successfully trained a MARL-based planner using this approach, and the important training techniques used in this study are reported. Statistical comparison of the MARL-based decentralized planner and an optimization-based centralized planner is conducted in simulation. The MARL-based and optimization-based planners are deployed to a CTAP prototype to address motion planning problems in the real world. Experimental results show that the MARL-based planner can achieve successful, decentralized, and online motion planning for a CTAP.

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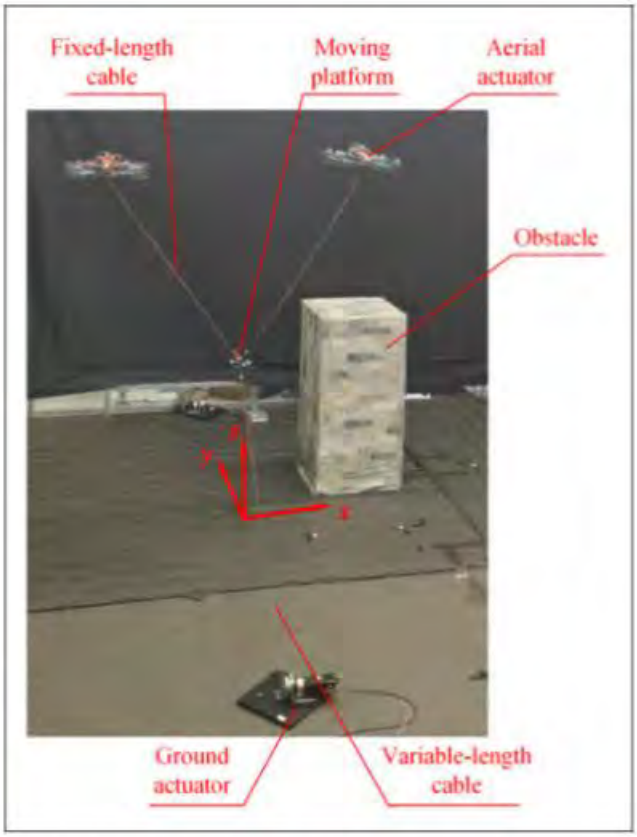

Figure 5. A cable-towed aerial platform prototype with two aerial actuators and two ground actuators in the real world.

How NOKOV Contributes to the Research

For experiments in the real world, a laptop with an AMD R5-5600U CPU and 16 gigabytes of memory is used for the optimization-based planner and the agent of ground actuators of the MARL-based decentralized planner. Two Jetson Orin Nano onboard computers with 8 gigabytes of memory are used for the two agents of aerial actuators of the MARL-based decentralized planner, respectively. The positional and geometric information of the moving plat-form, obstacle, and aerial actuators are measured by a NOKOV motion capture system. The length of variable-length cables is recorded by encoders.

Citation Zhu Y, Li L, Wang Y, et al. Online decentralized planning for a cable-driven parallel robot with aerial and ground actuators through multi-agent reinforcement learning[J]. International Journal of Advanced Robotic Systems, 2025, 22(5): 17298806251390589.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001598878500001

Optimal design and dynamic trajectory planning of a 2-DOF cable-suspended palletizing robot with parallelogram cable loop

Keywords

Cable-suspended parallel robot, Dynamic trajectory, Optimal design, Parallelogram cable loop, Palletizing

Abstract

To fabricate high speed, vast workspace, energy saving, and light weight of the logistics equipment, this paper proposes geometric and trajectory optimization methods for the cable-suspended parallel robot (CSPR), which is a two-degree-of-freedom (2-DOF) robot with a parallelogram cable loop, realizing the efficient palletizing operation with dynamic trajectories. Based on kinematic and dynamic models, the Torsion Resistance Ability Index (TRAI) and Torsion Resistance Consumption Index (TRCI) are proposed to indicate the torsion resistance performance of the CSPR with the parallelogram cable loop. A geometric optimization method is established with the reference dynamic trajectory, which provides an approach to carry out the optimal design of the CSPRs considering dynamic trajectories for the first time. For industrial palletizing, a planning method on the dynamic trajectory is proposed considering the obstacle avoidance based on the Fourier and Polynomial models. A prototype of the 2-DOF CSPR is established, and the palletizing experiments are carried out, providing a novel high-efficiency palletizing robot and technology.

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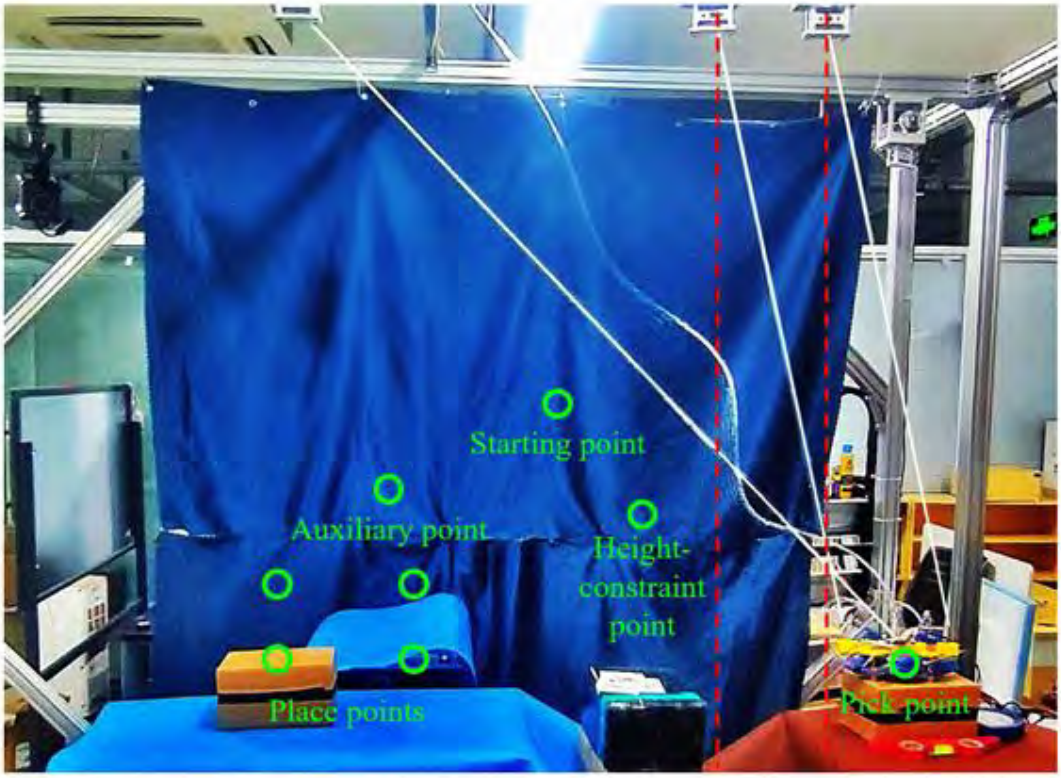

Fig. 7. CSPR grasps beyond its static workspace.

How NOKOV Contributes to the Research

The terminal position of the CSPR in the experiments were measured by the NOKOV motion capture system with the accuracy of 0.1 mm. The experiment and simulation results of Fourier trajectories are illustrated in Fig. 9 and Fig. 10. The experimental results show that the CSPR completed the proposed Fourier and polynomial trajectory as expected, and the obstacle avoidance requirement is achieved. Since the pulley kinematics is ignored and there are size errors in the adopted reconfigurable experimental platform, small position deviation appears near the endpoints.

Citation Liu H, Duan J, Shao Z, et al. Optimal design and dynamic trajectory planning of a 2-DOF cable-suspended palletizing robot with parallelogram cable loop[J]. Mechatronics, 2025, 108: 103330.

Link https://www.sciencedirect.com/science/article/abs/pii/S095741582500039X

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Performance analysis and optimization design of a rigid-flexible coupling hoisting robot considering cable deformation and random loading

Keywords

Rigid-flexible coupling hoisting robot, Performance optimization design, Dynamic model, Dynamic uncertainty quantification, Performance index

Abstract

To address performance issues caused by multi-source uncertainties of a rigid-flexible coupling hoisting robot (RFCHR), a performance optimization design method of the RFCHR considering cable deformation and random loading is proposed. The kinematic and dynamic models of the RFCHR are established, and the sources of uncertainty in cable deformation and random loading are analyzed, uncertain parameters are introduced into the dynamic model, and the dynamic uncertainty quantification of the RFCHR is achieved using the random interval perturbation method (RIPM). The reliability index is established based on the quantification analysis results. Subsequently, two performance indices including the workspace and static stiffness are established. A multi-objective optimization model is established based on performance indices, and the optimization design of the RFCHR is realized based on the optimization algorithm. Numerical examples demonstrate that the reliability, workspace, and static stiffness of the optimized RFCHR are improved by 10.7%, 13.4%, and 8.02%, respectively. In addition, the effectiveness of the RFCHR optimization design method is experimentally validated.

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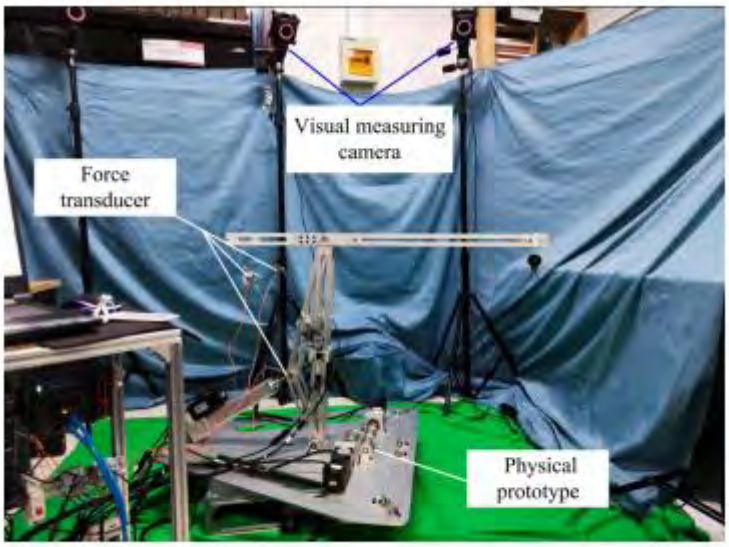

Fig. 16. Physical prototype of the RFCHR.

How NOKOV Contributes to the Research

As shown in Fig. 16, the physical prototypeof the RFCHR is constructed. in order to better verify the results of the optimization design, the robot configuration is adiusted ae.cording to the results of optimization design. Further, in order to track the motion of the RFcHR, the Nokov multi-camera visual capture system is tised, In addition, in order to accurately measure the dynamic response value of the RFcHR in the process of motion force sensors are installed in cables and the rigid rod.

Citation Zhou B, Li S, Zi B, et al. Performance analysis and optimization design of a rigid-flexible coupling hoisting robot considering cable deformation and random loading[J]. Mechanical Systems and Signal Processing, 2025, 223: 111903.

Link https://www.sciencedirect.com/science/article/abs/pii/S088832702400801X

Reconfiguration planning and structure parameter design of a reconfigurable cable-driven lower limb rehabilitation robot

Keywords

Cable-driven parallel robots · Rehabilitation robot · Motion capture · Reconfiguration planning · Structure parameter design

Abstract

Reconfigurable cable-driven parallel robots (RCDPRs) have attracted much attention as a novel type of cable-driven robot that can change their cable anchor position. The reconfigurable cable-driven lower limb rehabilitation robot (RCDLR) employs RCDPRs in lower limb rehabilitation to achieve multiple training modes. This paper investigates the reconfiguration planning and structural parameter design of the RCDLR. The RCDLR aims to fulfill the requirements of early passive rehabilitation training. Therefore, motion capture data are analyzed and mapped to the target trajectory of the RCDLR. Through dynamics modeling, the Wrench-Feasible Anchor-point Space (WFAS) is defined, from which an objective function for optimal reconfiguration planning is derived. The genetic algorithm is used to solve the optimal reconfiguration planning problem. Additionally, we propose the reconfigurability and safety coefficients as components of a structure parameter design method aimed at satisfying multiple target rehabilitation trajectories. Finally, numerical simulations are implemented based on the instance data and target trajectories to compute the specific structure parameters and verify the effectiveness of the reconfiguration planning method.

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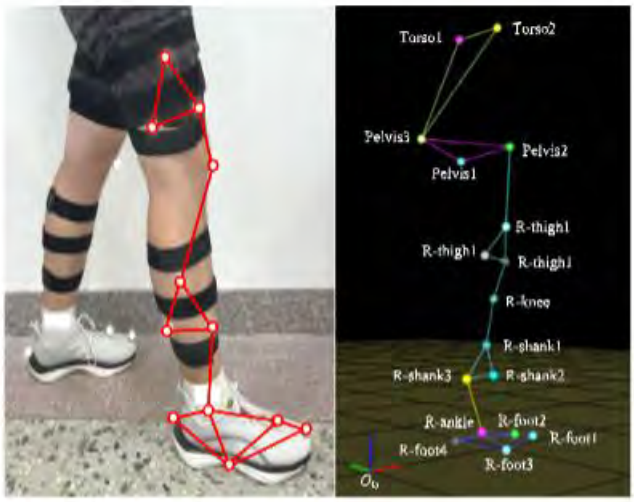

Fig. 1 Marker configuration and modeling

How NOKOV Contributes to the Research

2 Lower limb rehabilitation movementanalysis
Early-stage passive rehabilitation training involves the robotassisting the patient's limbs without relying on muscle forceto ensure consistent and effective exercise. Therefore, it isessential to determine the limb pose in actual rehabilitation movement and map it to the robot's target trajectory.Given that the RCDLR studied in this paper features a 3.DOF planar gait rehabilitation mode (GRM) and a 6-DOFspatial single-leg rehabilitation mode (SLRM). The NOKOV motion capture system is used to collect data on standingstill, gait walking, and hip internal rotation movements. Thehip internal rotation exercise requires the tester to begin ina standing position, then lift one leg to achieve a hip flexionangle of about 90°, subsequently move the lifted foot to attaina hip intorsion angle of about 40 degrees, and finally returnto the standing position. The approximate locations of themarkers on the tester are depicted in Table 2. Subsequently,the recorded data is processed by the Seeker software of the NOKOV systemto construct a marker model and addresslost frames. Figure l shows the marker configuration on thelower limb and constructed marker model.

Citation Li J, Wang K, Wang Y, et al. Reconfiguration planning and structure parameter design of a reconfigurable cable-driven lower limb rehabilitation robot[J]. Medical & Biological Engineering & Computing, 2025: 1-17.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001528299000001

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Serial–parallel cooperative assembly approach for precision micro-assembly of axial holes

Abstract

The assembly of high-density axial holes represents a crucial step in integrating highly sophisticated components for electronic equipment. This process faces two primary challenges: stringent precision requirements and the need for robust control during delicate adjustments. Given the miniaturization of components, manual assembly becomes inefficient. To address these challenges, this study introduces a novel dual-robot assembly system. The system incorporates a serial robot for force-controlled compliant assembly of precision axial holes, leveraging joint force sensors for direct force-feedback control to ensure enhanced positional accuracy. Additionally, a parallel robot facilitates precise positional adjustments, with its positioning accuracy further refined through kinematic calibration techniques validated through rigorous simulations. Ultimately, the established dual-robot assembly experimental platform successfully demonstrated the precision assembly of high-density axial holes, offering robust technical support for the precise integration of highly integrated components in electronic equipment.

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Figure 10. Parallel robot positioning accuracy optimization test bench.

How NOKOV Contributes to the Research

The positioning accuracy optimization testbed for parallel robots comprises a robot, calibration targets, and a motion capture system equipped with four cameras, as shown in Fig. 10.

Citation Dong L, Ma J, Cao J, et al. Serial–parallel cooperative assembly approach for precision micro-assembly of axial holes[J]. Mechanical Sciences, 2024, 15(2): 653-665.

Link https://ms.copernicus.org/articles/15/653/2024/

Serial–Parallel Mechanism and Controller Design of a Robotic Brace for Dynamic Trunk Support

Keywords

Dynamic trunk support; force control; robotic brace; serial–parallel manipulator;

Abstract

This article presents a robotic trunk support system that provides dynamic support and direct force/moment measurement, to assist trunk movement and train related core muscle groups. The proposed system has four degrees of freedom, three in the coronal plane and one in flexion/extension motion, which has a larger range than the existing robotic braces. The system was designed based on the serial–parallel mechanism. The serial module is responsible for the flexion/extension motion, and the parallel module is responsible for three degrees of freedom in the coronal plane. The kinematic modeling and singularity analysis of the parallel mechanism were discussed in detail. Then, the position control and force control of the serial control actuator were implemented, and the experiments were carried out to evaluate the performance of the controller. The effects on human body in force control were discussed and explained. A reduction in anterior muscles activation and an increase of dorsal muscles activation were exhibited when flexion torque was applied, while the trunk core muscle groups have opposite activation when extension torque was applied. The results indicate that the proposed robotic brace has potentials in the application to trunk core muscle groups training and corresponding rehabilitation.

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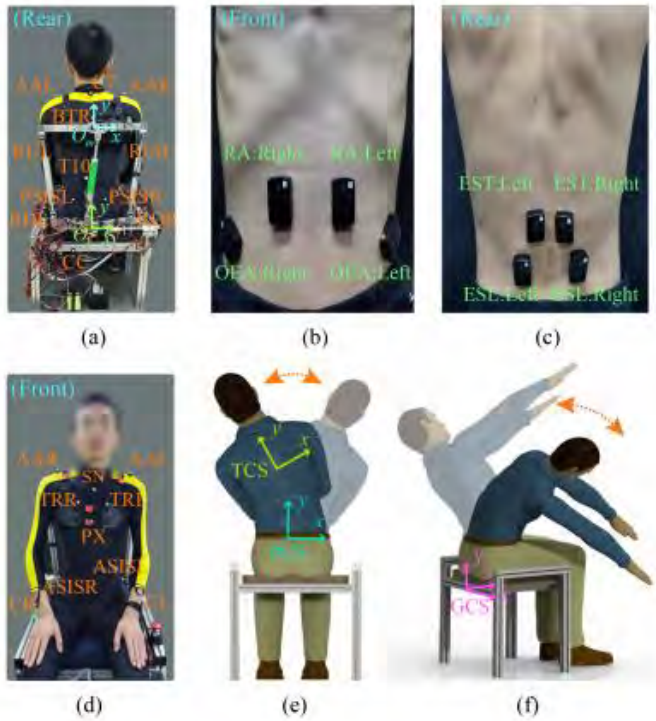

Fig. 6. (a) and (d) Placement of markers. (b) and (c) Placement of EMG electrodes. There are eight electrodes placed bilaterally on four muscle groups including EST, ESL, OEA, and RA. (e) and (f) Movement of lateral bending and the movement from right anterior flexion to left posterior extension, respectively.

How NOKOV Contributes to the Research

Kinematical Data Preprocessing: The motion capture camera system (MARS4H, NOKOV, China) was used to evaluate the performance of the RoboBDsys in terms of the accuracy of position at 100 Hz.

Citation Guo X, Zhou Z, Gao Y, et al. Serial–parallel mechanism and controller design of a robotic brace for dynamic trunk support[J]. IEEE/ASME Transactions on Mechatronics, 2022, 27(6): 4518-4529.

Link https://ieeexplore.ieee.org/abstract/document/9747946

Smooth Trajectory Planning for a Cable Driven Parallel Waist Rehabilitation Robot Based on Rehabilitation Evaluation Factors

Keywords

Waist rehabilitation robot, Trajectory planning, B-spline, Rehabilitation evaluation factor

Abstract

Rehabilitation robots can help physiatrists to assist patients in improving their movement ability. Due to the interaction between rehabilitation robots and patients, the robots need to complete rehabilitation training on a safe basis. This paper presents an approach for smooth trajectory planning for a cable-driven parallel waist rehabilitation robot (CDPWRR) based on the rehabilitation evaluation factors. First, motion capture technology is used to collect the motion data of several volunteers in waist twisting. Considering the impact of motion variability, the feature points at the center of the human pelvis are obtained after eliminating unreasonable data through rationality judgments. Then, point-to-point waist training trajectory planning based on quintic polynomial and cycloid functions, and multipoint waist training trajectory planning based on quintic B-spline functions are carried out. The corresponding planned curves and kinematics characteristics using three methods are compared and analyzed. Subsequently, the rehabilitation evaluation factors are introduced to conduct smooth trajectory planning for waist training, and the waist trajectory with better compliance is obtained based on the safety and feasibility of waist motion. Finally, the physical prototype of the CDPWRR is built, and the feasibility and effectiveness of the proposed smooth trajectory planning method are proved by numerical analysis and experiments.

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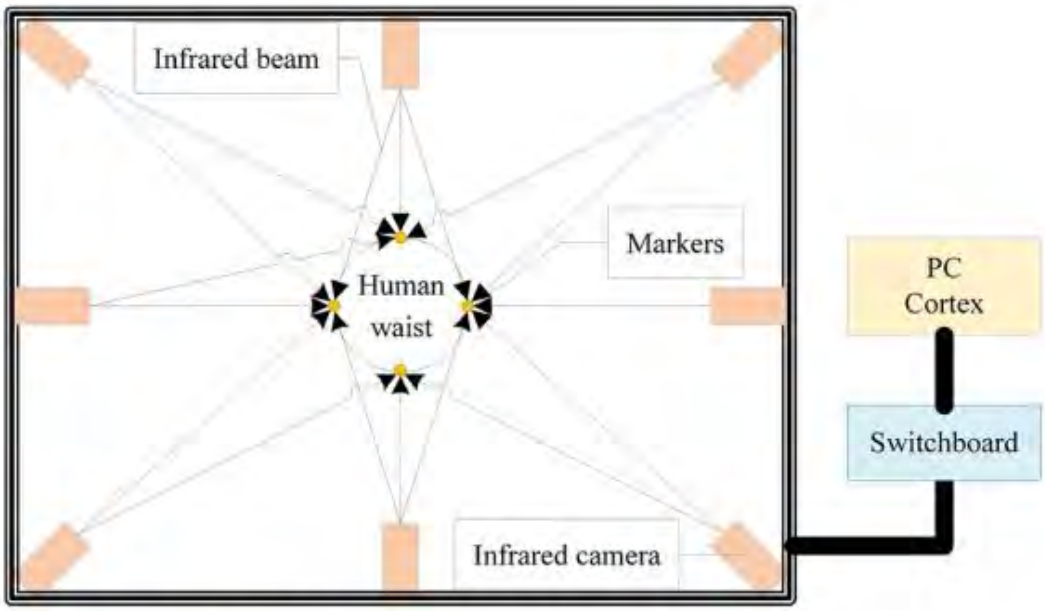

Figure 1 Principle of waist motion measurement

How NOKOV Contributes to the Research

20 male adults are chosen as the volunteers, and the Nokov optical motion capture system mainly composed of 8 infrared cameras is used to capture the motion data of the human waist [28]. 4 markers are evenly placed at the waist of volunteers, which are located at the front, back, left and right directions, respectively. The joints of upper and lower limbs are used as auxiliary points. Before the experiment, volunteers need to perform the slow counterclockwise rotation movement of the waist with the maximum range. The principle of waist motion measurement is shown in Figure 1.

Citation Li Y, Zi B, Sun Z, et al. Smooth trajectory planning for a cable driven parallel waist rehabilitation robot based on rehabilitation evaluation factors[J]. Chinese Journal of Mechanical Engineering, 2023, 36(1): 73.

Link https://link.springer.com/article/10.1186/s10033-023-00906-5

Torque Resistance Analysis and Dynamic Trajectory Planning for 3-DOF Cable Suspended Parallel Robot with Parallelogram Cable Loops

Keywords

Cable-suspended parallel robot (CSPR), torque resistance, dynamic trajectory, parallelogram cable loop

Abstract

This letter investigates the torque resistance performance and dynamic trajectory planning methods for general 3-DOF Cable Suspended Parallel Robots (CSPRs) with parallelogram cable loops, aiming to offer efficient and lightweight robotic equipment for industrial applications. The Torque Resistance Ability Index (TRAI) and Torque Resistance Consumption Index (TRCI) are proposed to evaluate the torque resistance performance of parallelogram cable loops and CSPRs. The Fourier model is adopted to plan the dynamic trajectory of the CSPR with the proposed TRAI and TRCI, which effectively minimizes oscillations and avoids overturns of the moving platform. The B-spline model is employed to implement more complex dynamic trajectories that go through additional constraint points, enhancing flexibility and adaptability. A prototype of the CSPR with parallelogram cable loops is established, and the proposed indexes and trajectory planning methods are verified with experiments.

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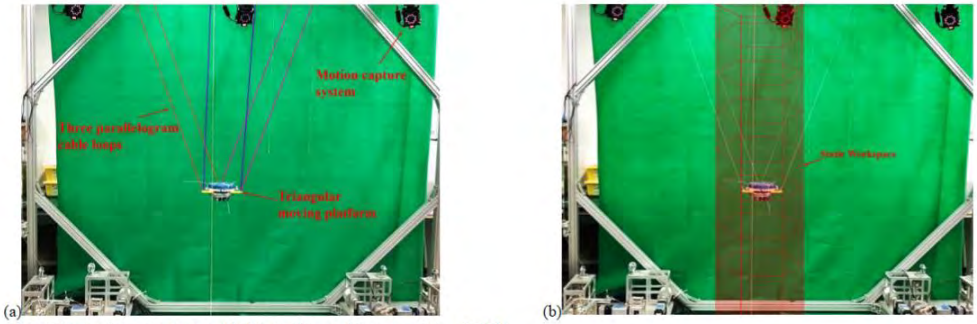

Fig. 4. (a) Experiment setup and (b) static workspace of the CSPR.

How NOKOV Contributes to the Research

According to the data collected by the NOKOV system, the tilt angle of the moving platform during the dynamic trajectory does not exceed 7°. Velocity and acceleration of the moving platform are depicted in Fig. 10(a) and 10(b). Experimental and simulated results exhibit good agreement, with the desired velocity and acceleration precisely achieved.

Citation Liu H, Duan J, Shao Z, et al. Torque resistance analysis and dynamic trajectory planning for 3-DOF cable suspended parallel robot with parallelogram cable loops[J]. IEEE Robotics and Automation Letters, 2024, 9(7): 6296-6303.

Link https://ieeexplore.ieee.org/abstract/document/10533681

Transformer-based segmented learning for kinematics modelling of a cable driven parallel continuum robot

Keywords

Parallel continuum robot, kinematics modelling, segmented learning, neural network

Abstract

Continuum robots with structural compliance exhibit significant operational potential in unstructured environments. However, theoretical kinematics modelling for continuum robots is complex due to their uncertain nonlinear characteristics. Although learning-based algorithms can effectively address the inherent challenges, unfortunately they frequently fail to capture internal information in robotic systems involving multiple spatial mappings, which reduces the accuracy of data-driven approaches in such applications. In this regard, we propose a segmented learning approach applied to kinematic modelling for a cable-driven parallel continuum robot (PCR), using Transformer networks to segmentally learn the mapping from task space to configuration space, and from configuration space to actuation space. Additionally, in order to evaluate the performance of the proposed approach, we employ multiple sets of neuralnetwork models and various segmented learning configurations in the experiments. The experimental results across different trajectories show that, the Transformer network model under the segmented learning approach achieves superior trajectory tracking accuracy, compared to state-of-the-art modelling approaches.

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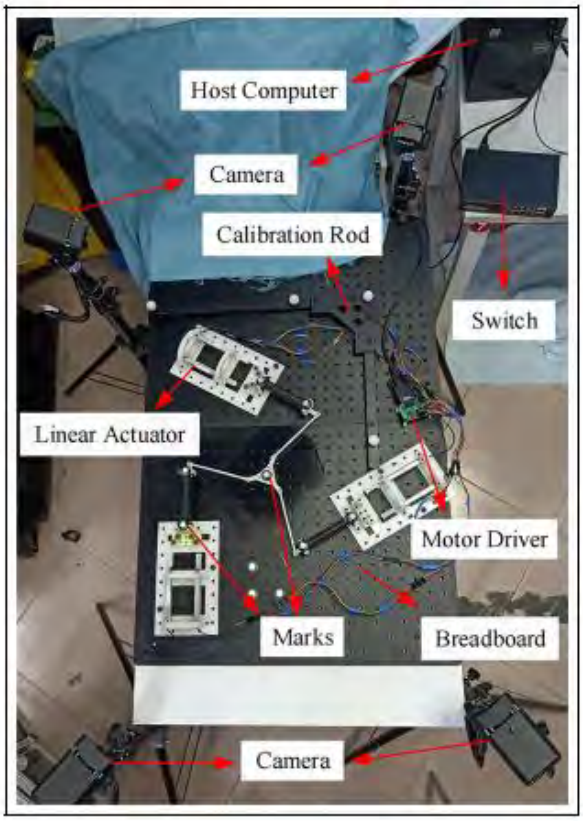

Figure 5. Experimental platform, including the PCR, motion capture cameras, motor driver and host computer.

How NOKOV Contributes to the Research

Calibration rods establish the camera's base coordinate system, and a switch facilitates communication between the host computer and the camera system. The motion capture camera, Pluto 1.3C from Beijing NOKOV Science and Technology, has a 3D accuracy of 1 mm. Four sets of cameras are arranged, achieving sub-millimetre calibration accuracy.

Citation Liu X, Wang Z, Li Z, et al. Transformer-based segmented learning for kinematics modelling of a cable-driven parallel continuum robot[J]. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2025, 239(8): 2942-2952.

Link https://journals.sagepub.com/doi/10.1177/09544062241306683

A Deep Learning-Based Approach for System Modeling of a Novel Cable-Driven Parallel Robot

Keywords

cable-driven parallel robot, system modeling, deep learning, data-driven design

Abstract

Cable-driven parallel robots (CDPRs) drive the end-effector through cables, offering advantages such as low inertia and high payload-to-weight ratio, which make them highly promising for applications in industrial and construction fields. However, the inherent flexibility of CDPRs introduces pronounced nonlinearities and uncertainties, posing significant challenges for system modeling and precise control. In this study, a novel type of CDPR, rigid-flexible hybrid parallel robot (RFHPR) designed for sorting and palletizing is investigated. To address the accurate system modeling challenges of RFHPR, this article proposes the CaRINet, a network combining gate recurrent (GRU) and transformer architecture for system modeling of cable-driven robots. For training CaRINet, a dataset is constructed from the RFHPR by applying the excitation trajectory generated by combining the finite Fourier series and quintic polynomial interpolation as the input, and collecting the corresponding end-effector position and motor torque as the output. Model performance studies are conducted to optimize CaRINet, and comparative experiments are performed against the conventional system identification method. The experimental results demonstrate the effectiveness of the CaRINet and exhibit higher performance compared to conventional identification methods.

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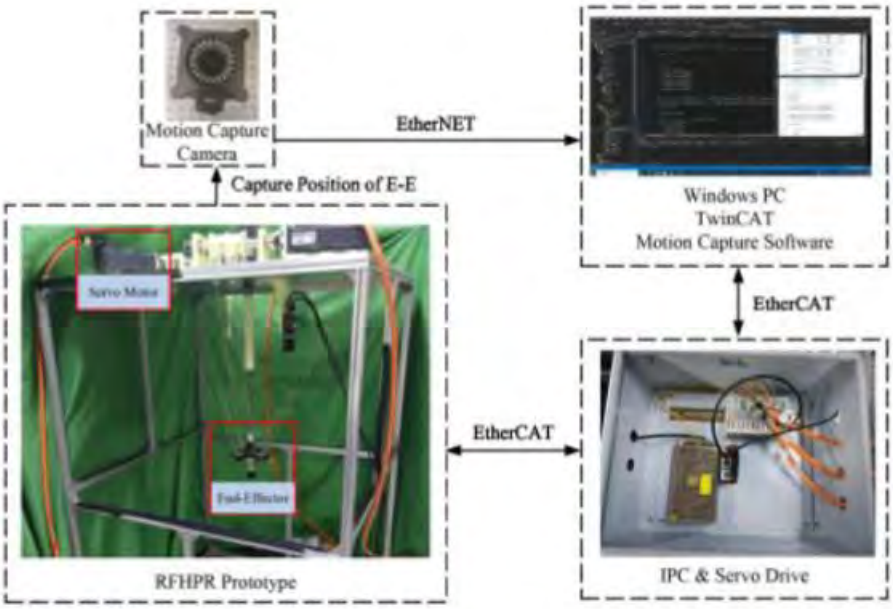

Fig. 4 Robot prototype

How NOKOV Contributes to the Research

Software. The experiment is based on TwinCAT platform and motion capture system software Nokov. Within the TwinCAT system, motor control is implemented using the position external setpoint generator in the Programmable Logic Controller (PLC) environment. TwinCAT also supports interprocess communication via the Automation Device Specification (ADS) protocol, allowing synchronization of the TwinCAT motion control and motion capture programs. The Nokov motion capture software collects position data from the cameras and provides a software development kit that supports multiple programming languages.

Citation Qian S, Zhao Z, Zhang T, et al. A Deep Learning-Based Approach for System Modeling of a Novel Cable-Driven Parallel Robot[J]. Journal of Mechanical Design, 2026, 148(11): 113301.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001746791400001

A Joint Optimization Framework for Workspace Analysis of an Underactuated Hybrid Pose Adjustment Robot

Keywords

underactuated cable-driven parallel robot, workspace analysis, force uniformity, attitude continuity

Abstract

Cable-driven parallel robots (CDPRs) are promising for construction automation owing to their large workspaces and high payload capacity. However, underactuated CDPRs (UACDPRs), which possess fewer cables than end-effector degrees-of-freedom, are generally underconstrained and suffer from issues such as pose ambiguity, discontinuous attitude transitions, and nonuniform cable force distributions. This article proposes a joint optimization framework for UACDPRs workspace analysis, applied to the hybrid pose adjustment (HyPA) robot, that simultaneously minimizes pose discontinuity and cable force variance. A system model that integrates the underactuated HyPA robot structure with horizontal motion platforms using Jacobian-based formulations is developed to enable accurate, offline workspace computation. Both simulations and hardware experiments validate the effectiveness of the method: the four-cable and five-cable actuated configurations show markedly reduced attitude differences (by up to 88.8%) and more uniform force distribution (fairness index up to 0.799), with a positioning error of 3.066 mm and force error of approximately 1.8% of the maximum tension. In contrast to conventional single-objective approaches, the proposed strategy offers a balanced solution and represents a step toward practical deployment of UACDPRs in construction automation, while highlighting the need for future work on real-time force redistribution and dynamic disturbance rejection to fully establish practical applicability.

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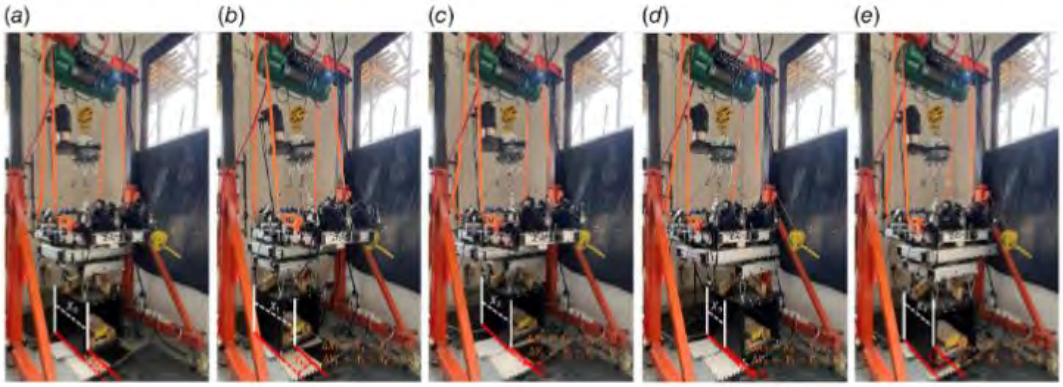

Fig. 13 Experimental validation of module positioning across the workspace. The module is shown at (a) the center and (b)–(e) four boundary positions under constraints: $f_{i,max} = 1000\,N$ and $h_{cp} = 0.93\,m$, where $X_1 > X_0$ $Y_1 > Y_0$, $X_2 > X_0$ $Y_2 < Y_0$, $X_3 < X_0$ $Y_3 < Y_0$, and $X_4 < X_0$ $Y_4 > Y_0$.

How NOKOV Contributes to the Research

*The prototype is instrumented with key sensors for data acquisition: force sensors in each cable measure real-time tension; motor encoders provide cable length feedback; an IMU on the hoisting platform monitors its leveling, ensuring inclination remains below 0.1 deg; and an optical motion capture system (**Nokov Motion Capture System, Beijing, China**) provides high-accuracy ground-truth pose data, as illustrated in Fig. 9.*

Citation Qian C, Song C, Li X, et al. A Joint Optimization Framework for Workspace Analysis of an Underactuated Hybrid Pose Adjustment Robot[J]. Journal of Mechanisms and Robotics, 2026: 1-11.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001715499500001

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Performance enhancement of a 3-DoF humanoid wrist: a dimensional optimization and experimental validation approach

Keywords

Humanoid wrist, Kinematic and static analysis, Genetic algorithm optimization, Object manipulation experiment

Abstract

Purpose

Wrist mechanisms are crucial for enhancing dexterity and load capacity in humanoid robots, but traditional designs often fail to balance load strength and maneuverability. This study optimizes a previously introduced three-degree-of-freedom (3-DoF) wrist mechanism using a 2PSS-U + RUR parallel configuration. The primary purpose of this study is to conduct multi-objective optimization of geometric parameters to improve overall dexterity and force equilibrium performance, thereby advancing humanoid robot capabilities in real-world scenarios through systematic parameter tuning.

Design/methodology/approach

The core dimensions of the wrist are analytically modeled in relation to key performance metrics, including dexterity and force equilibrium. Optimization is performed using the Non-dominated Sorting Genetic Algorithm II (NSGA-II), which generates a Pareto optimal solution set for joint angles and linkage ratios. Physical prototypes are fabricated with optimized dimensions, incorporating high-precision actuators and sensors. Experiments evaluate range-of-motion, torque output under controlled loads and dynamic object manipulation tasks to validate the improvements.

Findings

The optimized prototype achieved peak torques of 8.8 N-m for flexion/extension (F/E), 8.6 N-m for radial/ulnar deviation (R/U) and 1.5 N-m for pronation/supination (P/S), surpassing the non-optimized version. Object manipulation experiments demonstrated enhanced efficiency in complex maneuvers, with reduced energy consumption and improved accuracy in gripping and repositioning objects across orientations, confirming superior dexterity and force equilibrium in practical applications.

Originality/value

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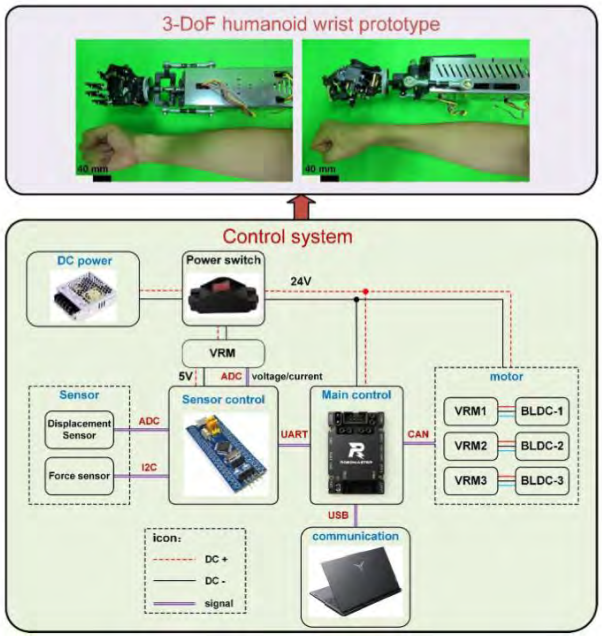
This work pioneers the application of NSGA-II for systematic optimization of parallel wrist mechanisms in humanoid robots, providing a replicable framework that integrates theoretical modeling with empirical validation. It addresses the gap in parameter tuning for such designs, offering enhanced performance metrics and a methodology that can be adapted to other robotic systems, thereby contributing to advancements in robotic dexterity and load handling.

Figure 5 The prototype and control hardware architecture of a 3-DoF humanoid wrist



How NOKOV Contributes to the Research

This subsection pertains to the 3-DoF humanoid wrist test platform developed in Section 5.1 to evaluate the range of motion and velocity of the humanoid wrist prototype. The final trajectory of the humanoid wrist prototype is assessed using the Nokov motion capture equipment from Beijing Metrics Technology Co., Ltd. to accurately ascertain the wrist's range of motion and velocity. The terminal equivalent mechanism, corresponding to the length of the human hand's middle finger and palm, is depicted as shown in Figure 6.

Citation Chen S, Wang S, Zeng H, et al. Performance enhancement of a 3-DoF humanoid wrist: a dimensional optimization and experimental validation approach[J]. Industrial Robot: the international journal of robotics research and application, 2026: 1-13.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001724380000001

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Integrated Pareto-based multi-objective optimization and topology-parameter design of a 3-RPR parallel mechanism for rail grinding applications

Keywords

Parallel mechanism; Mechanism parameter analysis; Multi-objective optimization; Fuzzy Comprehensive Evaluation; Rail grinding

Abstract

Abrasive belts exhibit significant advantages in rail grinding applications; however, current positioning adjustment systems for abrasive belt grinding units suffer from poor stiffness and low precision—two critical issues that severely restrict grinding quality. In contrast, parallel mechanisms with compact structure, high precision, and enhanced stiffness are ideal for addressing these challenges, so this study proposes a novel integrated design and optimization methodology for a 3-RPR parallel mechanism tailored to rail grinding applications, with core innovations overcoming limitations of existing approaches. These innovations focus on three aspects: a systematic topology design and parameter analysis framework establishing the relationship between hinge point parameters and key performance metrics; an integrated multi-objective optimization strategy combining the NSGA-II algorithm with fuzzy comprehensive evaluation eliminating subjective weight assignment and efficiently resolving conflicts among performance indicators; and comprehensive experimental validation establishing a direct link between theoretical optimization and practical performance improvement. In the research process, the mechanism topology was first determined based on screw theory and rail grinding task requirements, followed by analyzing parameter impacts on performance, and finally establishing an optimization model constrained by workspace, singularity avoidance, and driving force. Results show that the optimized 3-RPR mechanism achieves notable performance improvements: actuator lengths are reduced by 18.36%, 19.62%, and 1.21%, respectively, global dexterity is increased by 7.41%, and stiffness in X- and Y-directions is enhanced by 6.22% and 22.69%, respectively—directly addressing the stiffness and precision bottlenecks of the grinding unit positioning system. Notably, this study not only provides a theoretical basis for multi-objective optimization of parallel mechanisms and a practical methodology for task-specific mechanism design but also its parameter analysis and

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optimization logic can be extended to developing high-performance parallel mechanisms in other industrial scenarios, demonstrating broad application value.

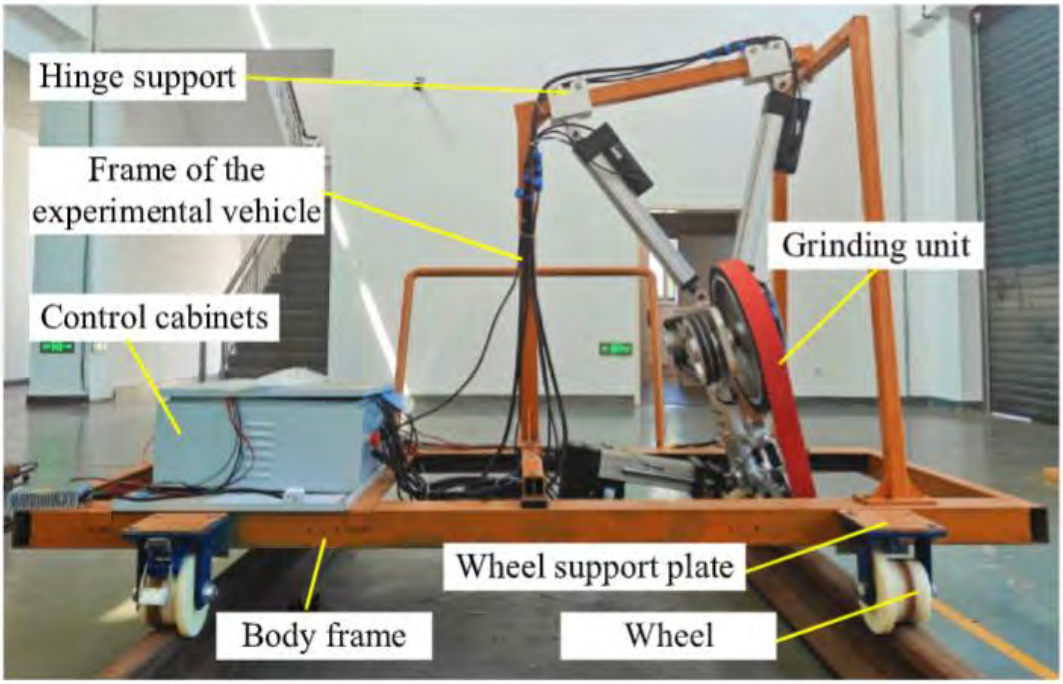

Fig. 14 Prototype of the grinding unit

How NOKOV Contributes to the Research

A NOKOV optical 3D motion capture system was employed to capture and analyze the movement patterns of reference points on the mechanism's moving platform. Initially, the optical cameras were positioned and the system was calibrated. Subsequently, marker points were placed, as illustrated in Fig. 15(a). The system recorded data on displacement, velocity, and acceleration changes as the moving platform transitioned from the initial posture (with limb lengths of 596 mm, 591 mm, and 512 mm) to the grinding posture of 0°, as depicted in Fig. 15(b).

Citation Hao L, Li J, Xu K, et al. Integrated Pareto-based multi-objective optimization and topology-parameter design of a 3-RPR parallel mechanism for rail grinding applications[J]. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2026, 48

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001718261900022

2-(U+UPS)PU+UPU 平动机器人腿机构设计与力速性能分析

关键词

机器人腿; 2-(U+UPS)PU+UPU 机构; 运动学模型; 速度性能; 静力学性能

摘要

以自由度少、末端无伴随转动特征且控制复杂度低为设计目标,提出了一种 2-(U+UPS)PU+ UPU 串并混联三自由度平动机器人腿机构。基于旋量理论分析了腿部机构的活动度并建立了腿部机构的运动学模型,仿真计算得到了腿部机构的末端工作空间和姿态变化特性,推导了末端速度雅可比矩 阵及力雅可比矩阵,分析得到速度和力学特性变化规律。开发了所提出腿部机构的原型样机,验证了其 可行性。

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图 10　实验设备及场地

Fig.10　The experimental equipment and experimental site

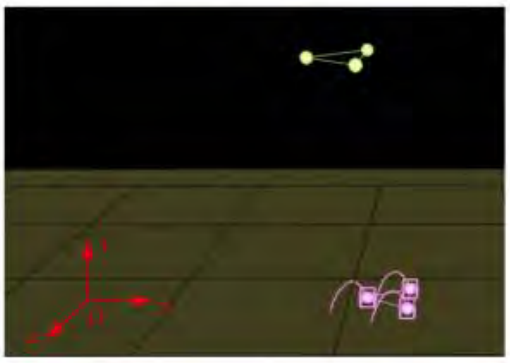

图 11　Seeker 软件输出窗口

Fig.11　The output interface of Seeker software

NOKOV 度量动作捕捉在研究中的应用摘录

使用 Nokov 动作捕捉系统对机器人腿的末端运动进行监测，以验证所提出机构的实际可行性,如图 10 所示。相关运动参数与 1.3 节仿真验证部分一致。
图 11 所示为 Nokov 动作捕捉系统监测软件 Seeker 的输出窗口,粉色曲线为实验所得末端轨迹。
研制了 2-(U+UPS)PU+UPU 平动机器人腿的原型样机,并通过 Nokov 动作捕捉系统 进行动作捕捉,验证了原型样机的可行性。

引用格式 罗自荣,徐毓泽,陈善军,等.2-(U+UPS)PU+UPU 平动机器人腿机构设计与力速性能分析[J].中国机械工程,2024,35(12):2193-2202.

链接

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2UU-PSU 上肢康复机构运动学与动力学研究

关键词

2UU-PSU；并联机构；位置反解；拉格朗日法；动力学

摘要

随着康复医疗技术的发展以及对上肢康复效果精准度要求的提高，对高效精准的上肢并联康复机构的研究愈发关键。提出一种新上肢并联康复机构，并针对其展开运动学与动力学层面的剖析。分析 2UU-PSU 自由度，采用闭环矢量法进行位姿求解并推导运动学方程，验证机构运动合理性；运用拉格朗日法构建动力学方程开展动力学分析；为证实运动学推导的精准性，搭建 2UU-PSU 实验平台并依靠 NOKOV 动作捕捉设备开展实验；最后建立自适应模糊 PID 控制，利用 ADAMS 和 MATLAB Simulink 对 2UU-PSU 机构进行动力学联合仿真。实验结果表明：2UU-PSU 上肢机构的动平台位姿测量最大均方根误差分别为 6.89%，1.81%和 9.73%；三条支链动力学仿真结果与理论数据的最大均方根误差别为 2.50%，2.40%和 2.97%。从理论与仿真分析以及实验验证结果来看，2UU-PSU 机构的运动学和动力学的均方根误差均处于较低水平，表明该机构在运动学和动力学方面具备合理性与可靠性，能够为相关康复机构的设计与研究提供有效依据，并为其他少自由度并联康复机构的动力学相关研究提供了参考。

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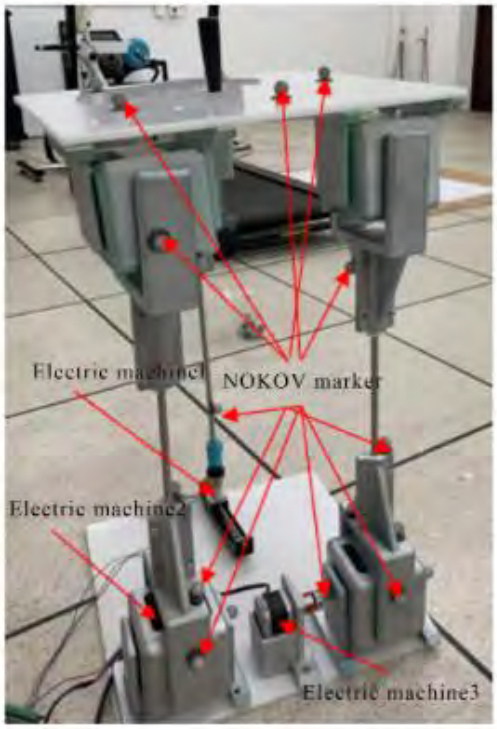

图 2　2UU-PSU 样机动捕贴点图

NOKOV 度量动作捕捉在研究中的应用摘录

为捕捉 2UU-PSU 动平台位置信息、角度随时间变化情况，采用 NOKOV 光学动作捕捉系统，使用时分别在 8 个摄像头内的 2D 视图进行噪点处理，接着依次进行 L 型和 T 型标定，为确保系统能够建立准确模型，Marker 点以非线性、非对称方式分布在刚体关键部位（如动平台的边缘、转角处等），使用双面胶固定，采样频率为 200 Hz，数据采集后选 CSV 数据存储格式。按照式（17）脉冲频率来控制电机转速，在样机处于运动状态时，电机借助机构驱动人体上肢产生相应运动，而 NOKOV 光学动作捕捉系统会对动平台的标记点开展实时追踪，并进行数据采集工作。

引用格式 崔冰艳,李文静,安福新,等.2UU-PSU 上肢康复机构运动学与动力学研究[J].光学精密工程,2025,33(06):884-894.

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飞机喷涂用索并联机器人智能系统研究

关键词

索并联机器人，LabVIEW，Android，数据采集，TCP

摘要

目前飞机喷涂行业普遍采用人工喷涂方式进行手工作业，但传统的人工喷涂方式存在诸多问题。这种喷涂方式需要操作人员长时间站立和持续操作，容易导致疲劳进而引发喷涂事故，有时还需要在高处进行作业，存在高空作业风险和恶劣工作环境的问题；同时，由于人为因素和操作技巧的不同，人工喷涂容易出现涂层厚度不均匀、喷涂遗漏等质量问题。为了弥补以上不足，顺应工业自动化发展，满足大规模生成需要，本文探讨索并联机器人在飞机喷涂领域的应用与发展前景，通过对四索悬挂式喷涂机器人进行研究，基于 LabVIEW 开发了一套智能系统，实现数据采集、控制、轨迹跟踪一体化设计，并根据喷涂场景需要，开发了针对 Android 系统移动终端的应用。主要研究内容概括如下：

基于四索悬挂式喷涂机器人系统构型，建立了运动学与动力学模型，利用 MATLAB 解算其运动学逆解并设计仿真试验得出了期望轨迹下绳索长度与拉力的变化趋势，最终验证了解算的正确性。

基于 LabVIEW 开发具有数据采集、电机控制、轨迹跟踪等功能模块的智能系统，利用.NET 与 TwinCAT 进行通信，结合 SDK 传输技术接收 NOKOV 的数据广播，并配合 DAQmx 实现拉力数据采集，完成一体化系统总体设计。

基于 Android Studio 开发移动终端应用，满足飞机厂房内喷涂需求，利用 TCP 通信协议接收并处理 PC 端智能系统传输的数据，同时能够反向发送控制指令。

针对所设计系统的功能模块，开展了对应的实验验证研究，通过控制动平台运动，根据得到的拉力数据和跟踪轨迹进行分析。实验结果验证了所开发的智能系统能够满足喷涂活动的基本需求，为索并联喷涂机器人人机交互系统设计与开发提供了参考。

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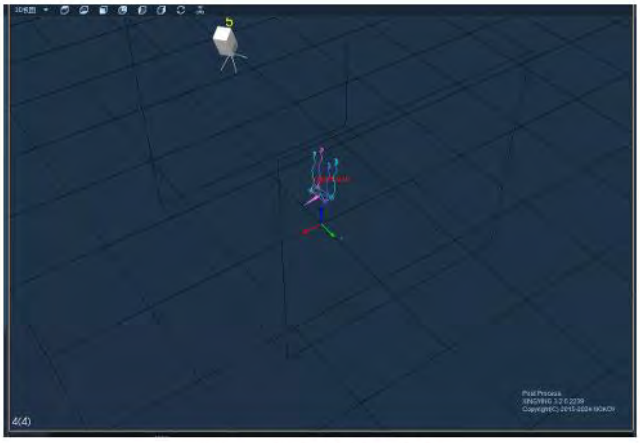

图 3.27 被捕获的运动轨迹

NOKOV 度量动作捕捉在研究中的应用摘录

使用 NOKOV 度量提供的动捕技术，包括其先进的传感器技术、摄像系统和专业的分析软件，能够实时捕捉、跟踪和量化动平台运动，为未来的喷涂工作奠定了基础。本系统依靠 NOKOV 成熟的摄像系统，通过配置摄像系统，包括调节摄像头的布局、分辨率、帧率等参数，将四个高分辨率摄像头安装在四索悬挂式喷涂机器人机构框架的上端四角，调整至合适角度，使其能够全方位捕捉被测物体即动平台的运动。随后通过对视频图像的处理和分析，识别和跟踪提前在动平台上标记的四个点，获取其运动轨迹。在对捕捉到的运动数据进行分析和处理时，需要提取关键的运动参数，如位置、速度、加速度等。通过数据分析，可以深入了解运动的特征和规律，评估运动的质量和效果。形影软件捕捉到的运动轨迹如图 3.27 所示。

引用格式 吴昶彤.飞机喷涂用索并联机器人智能系统研究[D].吉林化工学院，2024.DOI：10.27911/d.cnki.ghjgx.2024.000079.

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平面绳索牵引多体机器人设计与验证

关键词

绳索牵引；工作空间；配置优化；动力学分析

摘要

本文基于目前绳索牵引机器人的研究成果，利用绳索牵引机器人制造成本低、工作空间大、惯性小易于组装和重构等优点，设计出一款平面绳索牵引多体机器人，该机器人可组成平面串联多杆机构。然后推导出绳牵引多体系统绳索分布方式，并将推导出的关系应用到本文所设计的平面绳索牵引多体机器人的两杆和三杆机构上，计算出其合理的牵绳方式。在本文所设计的平面绳索牵引多体机器人中包含结构模块、硬件模块和软件模块（优化模块）。结构模块又可分为杆件模块、限位模块、关节模块和牵绳模块。硬件模块分为绳索驱动模块、运动控制模块和数据采集模块，用来控制电机从而控制绳索的收放同时采集拉力数据。本文使用零空间的方法求解系统工作空间，推导出此类系统力旋量封闭工作空间边界的解析解，求解出力旋量可行工作空间。在工作空间的求解的基础上提出一种优化方法，优化平面绳索牵引多体系统的电机位置和绳索在连杆上的牵引位置。在保证规划的轨迹在力旋量可行工作空间内的前提下，使得力旋量可行工作空间最大，此优化方法即为本文的优化模块。使用光学三维动作捕捉系统测量出上肢的尺寸和运动范围，按照测量数据规划三杆机构运动轨迹并使用优化方法进行配置优化。对此三杆机构使用 D-H 方法进行运动学分析，推导出运动学方程。计算出整个周期的绳索长度变化，并求解出绳索速度和绳索加速度。使用拉格朗日方程法进行动力学分析，然后计算出关节力矩和绳索拉力。最后，依照本文绳索牵引多体机器人的设计，搭建两杆机构和三杆机构进行实验，测出机构实际轨迹与理论轨迹进行对比，测出绳索实际拉力与理论拉力进行对比，验证前述运动学动力学分析和优化方法的正确性。

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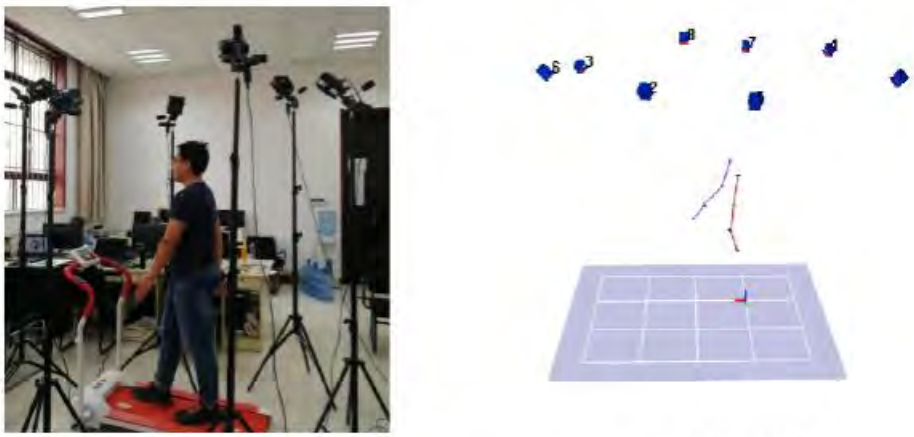

(a) 拍摄过程　　(b) 软件分析界面

图4.1 角度测量

NOKOV 度量动作捕捉在研究中的应用摘录

本节以人自然走动时的上肢向前摆动角度范围来规划三杆运动轨迹。本文采用 Nokov 光学三维动作捕捉系统来测量人走路时上肢向前摆动的角度和上肢长度等参数。该设备是一种高精度的三维测量仪器，测量精度可以达到亚毫米完全可以满足本次实验的精度要求。且因为三脚架的长度是可调的，所以测量范围可以根据需求调节杆长或添加增加镜头数量，所以该设备的测量精度和范围均满足要求。该系统由动作捕捉镜头 Mars2H 和分析软件组成，拍摄和处理如图 4.1 所示。

引用格式 何世凯.平面绳索牵引多体机器人设计与验证[D].西安电子科技大学，2019.DOI：10.27389/d.cnki.gxadu.2019.002642.

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全周期下肢辅助运动康复机器人关键技术研究

关键词

运动康复机器人;下肢辅助运动;不完全性脊髓损伤;全周期康复;人体运动意图识别;外骨骼控制;步态分析;

摘要

脊髓损伤是一种严重影响患者生活质量的神经系统疾病,我国每年约有 400 万左右新发病例。随着我国人口老龄化进程加速和交通、工业意外事故的增加,脊髓损伤患者整体数量持续上升。在所有脊髓损伤患者中,约有 60%为不完全性损伤(指脊髓神经组织部分损害但保留一定传导功能),这类患者常见症状包括下肢肌力下降、协调性差及平衡能力受限等,日常生活面临着无法独立行走、身心健康和生活质量严重受损等问题,康复需求迫切。由于康复过程漫长且复杂,患者康复需求具有明显的阶段性和个性化特征,对下肢功能康复设备提出了高效性与适配性的双重要求。然而,传统全周期下肢辅助运动康复机器人普遍存在功能适配性不足以及控制策略自适应性差等技术难题,限制了其实际应用范围。本文围绕不完全性脊髓损伤康复过程中的关键技术需求,从机器人执行机构设计、人体运动意图识别、控制策略优化及步态评估体系等方面展开深入研究,提出系统性解决方案。 (1)针对传统全周期下肢辅助运动康复机器人功能适配性差和成本高的问题,基于 TRIZ 理论进行问题分析,得出 4 个关键子问题,应用矛盾矩阵和最终理想解等解题方法,形成 12 种备选方案。通过综合评价,确定 5 种优选方案构成下肢辅助运动康复机器人的整体设计,核心是“分阶段执行机构”解决方案,为康复早期(护理阶段)和中后期(下肢功能恢复阶段)分别配置专用执行机构,实现功能与成本的优化平衡。 (2)针对当前康复早期舒适性不足的问题,采用 TRIZ 分析中提出的解决方案,设计一种基于仿人抱取动作的运动康复机器人护理执行机构,为康复早期患者提供安全、高效的移乘护理支持。通过 3D 动作捕捉系统分析人类抱取行为路径,设计了一种模块化的 3UPS+UPR 并联机构,通过仿真分析与样机实验测试,该运动康复机器人护理执行机构在工作空间、运动平稳性和舒适性等核心指标上的显著优势。 (3)针对康复中后期外骨骼系统人体运动意图识别问题,采用 TRIZ 分析中提出的解决方案,提出一种结合信号插补与不确定性感知人体的运动意图识别方法。在复杂康复训练场景下,通过插补数据中的缺失部分并提供不确定性量化评估,结合深度学习模型精准识别患者运动意图。实验结果表明,该方法即使在高数据缺失场景下仍表现出较高识别精度与鲁棒性,为康复个性化训练和控制系统信号的高质量输入提供了智能化支撑。 (4)针对康复中后期外骨骼系统控制个性化问题,采用 TRIZ 分析中提出的解决方案,提出一种离线学习与在线微调相结合的外骨骼控制方法,采用力位混合控制采集高质量的状态-动作对,同时可针对患者调整主被动训练模式,采集后使用离线强化学习获取基础控制策略,结合患者在实际训练中的实时交互数据进行小幅在线调整,构建闭环自适应控制框架。实验结果表明,该方法能够有效提升步态对称性、优化辅助力输出并降低代谢能耗,适应患者动态变化的个性化康复需求。

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(5)针对步态评估系统在康复过程中的精度和适用性矛盾,采用 TRIZ 分析中提出的解决方案,设计一种基于单目摄像头+深度学习的步态评估体系。结合深度学习模型实现步态特征的精准提取与人体 3D 运动姿态估计,量化患者步长、步态周期及对称性等核心指标,实验验证表明其精度接近传统高精设备,且具备更强的普适性与快速部署能力。 本文通过以上研究显著提升了不完全性脊髓损伤康复中辅助设备的关键技术水平,成功解决了康复机器人在不同阶段的适配性与个性化问题,为开发普适性、高性能的运动康复机器人应用提供了技术支撑与理论依据,对提高脊髓损伤患者康复效率和生活质量具有重要现实意义。

图 29 抱取动作实验布置

NOKOV 度量动作捕捉在研究中的应用摘录

(1)仿人抱取动作的实验设计与方法
本研究采用 NOKOV 光学三维动作捕捉系统，对护理者在完成抱取转移动作时的动态特性进行测试与数据记录，并基于仿人动作模型进行实验分析。实验招募了 5 名被护人员，年龄集中在 20-35 岁，身高范围为 1520 mm 至 1810 mm，体重从 53 kg 至 85 kg 不等，所有被试者均符合不完全性脊髓损伤患者的典型参数特征，如表所示。同时，为保障护理动作实施的稳定性和科学性，实验选择了经验丰富的男性护工为护理操作的参考对象。所有参与人员在测试前均避免剧烈活动，并确保充分休息以消除生理差异的潜在影响。

引用格式 李家宝.全周期下肢辅助运动康复机器人关键技术研究[D].安徽理工大学,2025.DOI:10.26918/d.cnki.ghngc.2025.000027.

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柔性上肢康复机器人控制系统研究

关键词

康复机器人；动作捕捉；运动意图；康复评定；运动规划

摘要

我国已进入老龄化社会，心脑血管疾病和脑卒中等发病率不断上升，其中约有 85%的患者伴有上肢功能障碍。传统的康复训练方法是康复治疗师对患者进行手把手、一对一、连续并反复的被动训练，存在效率低、控制精度差、患者被动接受治疗主动性差等问题。因此，研发上肢康复机器人辅助患肢进行康复训练，不仅可以缓解康复医师短缺的社会难题，而且有利于缩短康复时间并提升康复效果，具有重要的理论意义和需求背景。本论文针对现有的末端牵引式和外骨骼康复机器人存在的惯性冲击大、控制柔性差，训练动作单一等问题，结合自主研制的绳牵引式上肢康复机器人本体，开展柔性上肢康复机器人控制系统研究，以期实现该机器人在被动、主动等不同训练模式下的柔顺控制。

论文主要研究工作是：

1、柔性上肢康复机器人的运动学分析和运动规划。结合柔性上肢康复机器人的混联机械结构，进行了正运动学和逆运动学分析，建立了康复机器人关节之间的空间关系。研究了临床上肢康复动作的运动特性，采用动作捕捉技术得到了不同康复动作的速度和加速度曲线。采用笛卡尔空间规划方法进行轨迹规划，并采用 matlab 建立了康复机器人模型，进行了运动仿真，结果表明：机器人的轨迹平滑，运动柔顺，可实现平稳的康复训练。

2、柔性上肢康复机器人不同训练模式下的控制方法研究。对于被动训练，采用 Jog 运动模式和 Follow 运动模式实现多电机的协调性控制，同时，通过圆弧插补算法提高康复轨迹的准确度，通过设置运动平面检测方法确保被动训练动作的有效性；对于主动训练，采用动作捕捉技术获取上肢的实时运动状态，并结合绳索拉力值判断运动意图，通过 PVT 运动规划实现康复机器人的跟随控制，并使用 PT 运动进行速度规划，实现补偿控制。

3、柔性上肢康复机器人控制系统实现。完成了机器人控制系统的硬件、软件系统开发，实现了机器人的柔顺控制。硬件方面，搭建了基于 Nokov 的动作捕捉系统，以及控制系统的硬件选型；软件方面，采用 C/S 架构开发了上肢康复训练人机交互软件系统，主要包括运动控制层、数据交互层、人机交互界面层。同时，基于案例推理的方法设计了上肢康复评定系统，可结合患肢的运动功能自动生成康复治疗方案。

4、柔性上肢康复机器人实验研究。搭建了绳牵引式上肢康复机器人实验平台，完成了被动训练、主动训练和上肢康复评定系统的实验研究。结果表明：被动康复训练模式下，单关节、多关节动作的最大绝对误差分别不超过 5mm 和 6mm，且控制系统稳定；主动康复训练模式下，机器人能够实现良好的跟随控制和补偿控制，系统响应延迟不超过 5ms。

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图 4.1 动捕镜头

表 4.1 动捕镜头参数表

型号	分辨率	像素数	频率	延迟	视场角	镜头
Mars 2H	2048×1088	2.2MP	340Hz	2.8ms	56.3×43.7°	8mm

NOKOV 度量动作捕捉在研究中的应用摘录

常见的光学式动作捕捉系统由 6-8 个数字镜头环绕捕捉场地排列，相机重叠的捕捉区域就是能够被捕捉的动作范围\[60]。为了让捕捉效果达到最好，测试者通常穿上单色服或者动捕服，然后在身体需要捕捉的位置，如肩关节、肘关节等关节位置布置反光的 Marker 点，捕捉系统识别并且处理这些 Marker 点，从而得到人体关节的运动数据。综合考虑，本论文选用北京度量科技公司的 NOKOV 动作捕捉系统搭建动捕系统。

Nokov（度量）光学三维动作捕捉系统由动作捕捉镜头、动作捕捉软件和动作捕捉附件构成。其中，动作捕捉镜头如图 4.1 所示，参数如表 4.1 所示。捕捉镜头内置图像处理器，采用十位灰阶深度和 GrayScale 图像处理算法\[61]的双优组合， Nokov（度量）光学动作捕捉系统可以进行亚毫米级的运动捕捉。动作捕捉到的所有数据经云计算\[62]之后传输，镜头连接采取并联的方式，数据能够实时迅速的传输到客户端进行分析。

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柔性上肢康复机器人路径规划及实现

关键词

柔性上肢康复机器人；运动分析；路径规划；功能实现

摘要

目前,我国老龄化人口基数不断增长,因脑卒中导致的上肢偏瘫患者日益增多,康复需求巨大。临床试验表明:在病发后的前三个月里,患者接受康复治疗,其效果是最佳的,治疗总有效率达到 92.4%。因此早期的康复训练是非常有必要的。本文依托重庆市人工智能技术重点研发项目,对柔性上肢康复机器人进行路径规划和功能实现。由于实验室现有的康复样机在运动过程中存在模式单一、不平稳等现象,而且忽略了柔绳特性对上肢运动的影响,本文针对样机的不足进行了运动分析,设计了多关节组合运动路径方案,进行了合理的运动路径规划,并利用 CPAC 控制器和虚拟现实技术加以实现。首先,立足于上肢康复理论,总结人体上肢肩、肘两关节的运动自由度和运动范围,通过实验室现有的康复样机结构特点,分析上肢康复样机运动原理,对上肢复杂动作的逆向研究,结合实验室上肢康复样机,设计多关节组合康复运动方案。其次,对柔性上肢康复机器人进行运动学分析和建立柔性上肢康复机器人动力学模型。分析柔绳的受力特性,利用牛顿-欧拉法和拉格朗日法建立柔性上肢康复机器人力学模型,并对柔绳牵引下的上肢康复运动进行动态分析,为后期的机器人末端运动规划奠定基础。接着,对多关节组合运动进行路径规划。通过对柔性上肢康复机器人运动学和动力学分析与求解,利用余弦多项式函数、三次多项式插值和五次多项式插值对上肢运动进行运动规划分析,为下一步上肢进行平稳的康复训练做准备。最后,上肢康复动作的实现。利用 CPAC 控制器,搭建上肢康复机器人实验平台,配置多关节组合运动参数,结合 NOKOV 三维光学动作捕捉系统,对上肢运动路径实时跟踪监测,再结合虚拟现实技术,模拟真实的训练场景,对上肢康复运动进行验证与实现。

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图 5.5 Mars 系列动作捕捉镜头

表 5.1 动捕镜头参数表

型号	分辨率	像素数	频率	延迟	视场角	镜头
Mars 2H	2048×1088	2.2MP	340Hz	2.8ms	56.3×43.7°	8mm

NOKOV 度量动作捕捉在研究中的应用摘录

本论文研究目标是基于实验室现有的绳牵引式柔性上肢康复机器人，对康复机器人的运动学和动力学进行分析，设计上肢康复运动方案，运用多种运动规划算法对柔性上肢康复机器人运动进行路径规划，在 CPAC 控制器中搭建 PLC 运动控制平台，结合 NOKOV 动作捕捉系统，对上肢康复机器人运动轨迹进行控制与跟踪，验证运动的平稳性，最后结合虚拟现实技术，开发康复训练趣味游戏，提高康复训练效果，验证上肢康复运动的准确度。

为了实时获取上肢在康复运动过程中的位置变化情况，本实验采用了北京度量科技有限公司的 NOKOV（度量）光学三维动作捕捉系统实时获取上肢在关节空间中的变化，该系统由动作捕捉镜头和动作捕捉处理软件两部分组成。

NOKOV（度量）光学动作捕捉镜头，如图 5.5 所示，内置图像处理器，以进行亚毫米级的运动捕捉，所有数据经云计算之后传输，镜头连接采取并联方式，保证了数据的实时迅速，让用户可以在同一时间观察到目标的每一个动作。

引用格式 杜豪.柔性上肢康复机器人路径规划及实现[D].重庆理工大学，2020.DOI：10.27753/d.cnki.gcqgx.2020.000507.

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绳牵引并联喷涂机器人运动控制系统设计与研究

关键词

绳牵引并联机器人，喷涂机器人，性能分析，控制系统

摘要

绳牵引并联机器人区别于传统并联机器人的显著特征在于，它采用柔性绳索而非刚性杆作为传动元件。这种设计不仅保持了并联机器人的高负载能力，还显著扩大了其工作空间，使其具有更广泛的应用潜力。本文提出将绳牵引并联机器人与传统喷涂机器人的功能相结合，开发一款新型航空涂装作业喷涂机器人。根据课题要求，本文设计并搭建了一款绳牵引并联机器人原理样机，并为之开发了一种鲁棒 PD 控制方法，进行了相关验证实验。本文具体工作内容如下：

首先，提出原理样机的整体设计方案，详细描述静平台、驱动机构、绳索导向机构的设计方案，以及伺服系统、绳拉力数据采集系统以及位姿测量系统的选型依据，并完成原理样机硬件搭建工作。同时，为实现原理样机的基本调试功能，为其开发了单轴和多轴调试软件。

其次，针对原理样机开展运动学、动力学建模工作，通过 MATLAB 仿真实验的方式，对正逆运动学以及动力学模型正确性进行验证，为后续的控制方法的开发工作奠定数学基础；同时，针对原理样机进行静力学分析，通过 MID 算法对完全约束绳牵引并联机器人的绳拉力进行求解，在此基础上对绳牵引并联机器人的工作空间和全局运动性能两项指标进行分析。

然后，针对绳牵引并联机器人的控制方法进行研究。开发了一种鲁棒 PD 控制方法，通过李雅普诺夫第二法对控制律的稳定性进行证明，并通过 MATLAB 仿真的方式，验证其有效性。

最后，在对原理样机的绳拉力采集系统和伺服系统进行校准和调试之后，进行功能验证实验，实现对机器人的实际控制，对本文所开发原理样机的基本运动功能进行了验证。

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图 2.8 动作捕捉系统

NOKOV 度量动作捕捉在研究中的应用摘录

动平台位姿测量系统选用了 NOKOV 公司研发的动作捕捉系统，如图 2.8 所示，相比于传统的工业视觉方案，动作捕捉系统的测量更加精确，帧率更高，该系统已经广泛应用于步态分析、仿生机器人开发，移动机器人运动规划与集群系统研究当中，展现出优秀的可靠性和良好的易用性。同时，NOKOV 公司提供的"形影"软件具备将数据实时广播的功能，可通过官方开发的 MATLAB、LabView、C#等高级语言 SDK 进行接收，通过该功能即可将动捕系统集成至控制系统当中。

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绳索牵引机器人位姿误差分析与补偿研究

关键词

绳索牵引机器人；误差建模；灵敏度分析；参数辨识；误差补偿

摘要

绳索牵引机器人是使用绳索代替连杆作为驱动元件的机器人,具有安装方便、工作空间大等优点。本文研究的机器人为绳索牵引多体机器人,将应用于康复医疗领域。绳索作为柔性体,并不能像刚体一样进行精确的位姿控制,导致绳索牵引机器人更易产生误差。为了提高其使用性能,通过补偿来提高末端执行器精度是很有必要的。为了深入了解绳索牵引机器人误差形成原因并最终通过补偿降低误差,本文以平面绳索牵引多体机器人为研究对象,在误差建模、灵敏度分析、参数辨识以及误差补偿方面进行了深入研究。首先,设计绳索牵引多体机器人结构方案,分析运动学规律,并对其进行轨迹规划。采用 D-H 法和矢量封闭原理建立其运动学正逆解模型,在 Creo 软件中建立绳索牵引三杆机器人模型,采用 Adams 软件分析验证其运动学的正确性。其次,进行绳索牵引机器人的误差建模和灵敏度分析。分析了绳索牵引机器人误差来源,其中包括零位误差、绳索弹性误差、末端执行器几何参数误差及绳索出索口位置误差等。采用矩阵微分法推导了误差模型,通过 Matlab 软件仿真验证了该模型的正确性。利用灵敏度分析方法分析了各类参数对末端执行器精度的影响程度,联合 Isight 软件和 Matlab 软件仿真验证了该灵敏度分析方法的有效性。最后,研究了绳索牵引机器人的误差补偿方法,并对其进行了实验验证。搭建了实验平台,采用最小二乘法对几何参数进行参数化辨识,将辨识的结果带入修正的运动学模型中。应用 Nokov（度量）目标运动跟踪装置采集末端执行器的运动轨迹,采用运动学标定补偿法对绳索牵引机器人进行补偿。样机实验表明最终补偿后的误差减小到补偿前的 20%,表明本文建立的误差模型及补偿方法有效的提高了末端执行器位姿精度,同时对其它绳索牵引机器人的误差补偿也有一定的指导意义。

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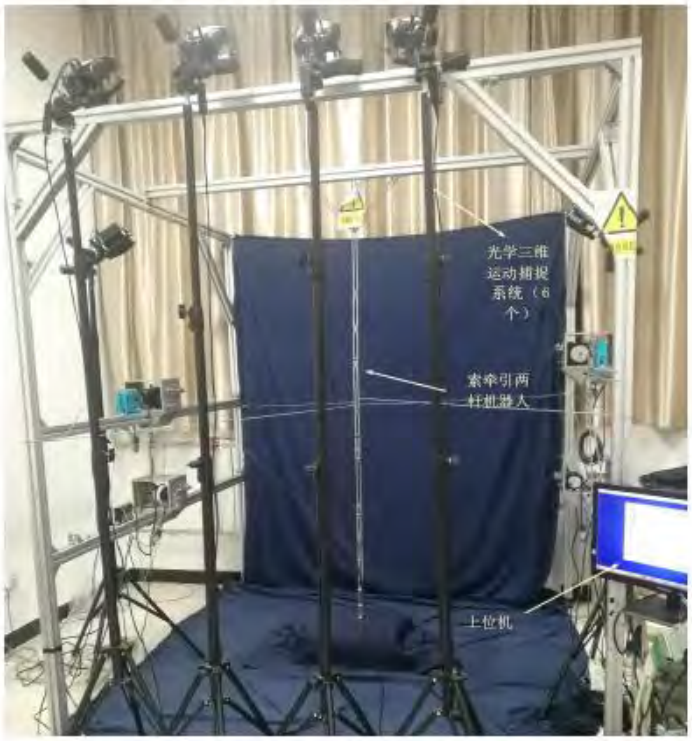

图 4.1 机器人标定实验平台

NOKOV 度量动作捕捉在研究中的应用摘录

本次标定实验采用的实验工具由平面绳索牵引两杆机器人、 Nokov（度量）目标运动跟踪装置和上位机组成，如图 4.1 所示。目标运动跟踪装置作为测量装置来采集机器人末端的实际位置，在计算机中对采集的数据进行处理辨识出运动学参数误差，然后完成对机器人的误差补偿，再进行一次补偿实验，最后使用目标运动跟踪装置来采集补偿后的位置点，验证补偿效果。

本次实验采用目标运动跟踪装置做为测量设备，该设备是一种高精度的三维测量仪器，测量精度可以达到亚毫米，本次标定实验所需的测量精度为毫米级别，所以该设备完全可以满足本次实验的精度要求。因为三脚架的长度是可调的，所以测量范围可以根据需求调节杆长和添加测量设的个数，所以测量精度和范围均满足要求。步进电机驱动定长绳索实现末端执行器的运动。

Nokov（度量）目标运动跟踪装置主要是由动作捕捉镜头、动作捕捉软件和动作捕捉附件构成。可根据场地条件和测试环境选配相应镜头数量和搭建方案，并进一步根据分辨率、频率、精度要求选配相应型号的镜头，所用仪器的型号如下。

引用格式 赵萍.绳索牵引机器人位姿误差分析与补偿研究[D].西安电子科技大学，2019.DOI：10.27389/d.cnki.gxadu.2019.000434.

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绳索驱动柔性下肢步态康复机器人设计与分析

关键词

下肢步态康复;绳索驱动;柔性康复机器人;被动康复;

摘要

康复机器人在提高康复效率和改善患者生活质量方面具有显著作用，同时面对全球人口老龄化的挑战，展现出广阔的应用前景和重要的研究价值。针对现有下肢康复机器人存在人机兼容性、训练模式及针对性等方面的不足，提出一种绳索驱动柔性下肢步态康复机器人。首先，介绍下肢康复机器人的整体结构，进行运动学分析，得到力封闭下肢位姿与绳索数据之间的关系。针对不同患者兼容性不够全面的问题，根据关节轨迹以及运动学分析建立了一种兼容性更强且数据获取更方便的绳索数据模型。之后，通过动作捕捉实验获取人体下肢髋关节和膝关节在行走过程中随时间的变化轨迹。搭建实验平台并开展康复实验研究，将绳索数据模型得出的绳索长度变化规律与实际进行对比，验证绳索数据模型的可行性。通过绳索拉力辨识实验与被动康复实验，确立绳索拉力与步态周期的时间映射关系，检验下肢步态康复机器人被动康复训练的可行性与准确性。实验结果表明，所提出的下肢步态康复机器人可以通过绳索数据模型在步态康复过程中实现精准的运动轨迹控制。这种技术的应用有助于提高康复训练的效果和安全性，为患者提供更加个性化和高效的康复方案。

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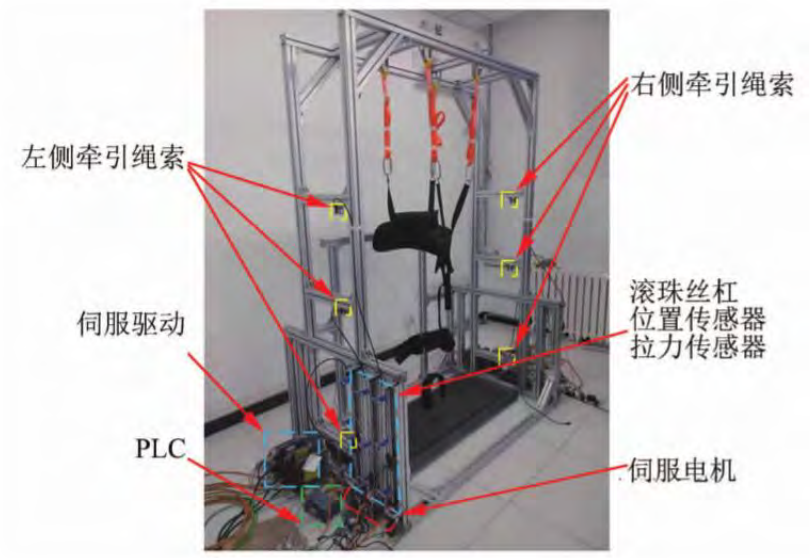

▲图 7　下肢步态康复机器人实验平台

NOKOV 度量动作捕捉在研究中的应用摘录

4 关节轨迹的获取
关节轨迹是髋关节角和膝关节角随步态周期的变化规律,获取关节轨迹对改进康复过程具有重要意义。具体来说,使用光学式动作捕捉系统来获取人体下肢膝关节和髋关节的变化函数,并将这些变化函数代入式(14)中,从而获得更优化的绳索长度变化函数。这样可以使整个康复过程更具针对性和有效性。
光学式动作捕捉系统,它通过光学原理来完成物体的捕捉和定位。光学镜头捕捉固定在人体或是物体上面的 marker 位置信息来完成动作姿态捕捉。光学式动作捕捉依靠整套精密而复杂的光学摄像头来实现,它通过计算机视觉原理,由多个高速摄像机从不同角度对目标特征点进行跟踪来完成全身的动作捕捉。
光学动作捕捉可分为被动式和主动式两种,红外 NOKOV 动作捕捉系统是一款被动式光学动作捕捉系统,它通过镜头本身自带灯板发出特定波长的红外光,照射到 marker 上,marker 通过特殊反光处理,可以反射镜头灯板发出的红外光,这样镜头就能在视野里捕捉记录该 marker 的运动轨迹,可以用于获取精确的人体下肢运动学数据。因此,进行动作捕捉实验可以获得下肢髋关节和膝关节的关节角随时间的周期变化函数。

引用格式 王志军,杨悦,马文文,等.绳索驱动柔性下肢步态康复机器人设计与分析[J].机械设计与研究,2025,41(04):137-145.DOI:10.13952/j.cnki.jofmdr.2025.0281.

链接

https://kns.cnki.net/kcms2/article/abstract?v=yqBhao7Q9gxsUex4Ef4Muexz95MVNwWQnYpcLOUz4pjuKXP_0JLb-7b_yPrp2pkIS2xc665FY9RSukQNSIAovcbN3EfBgA1QzUvVwY-6qv4zoZYgXgjDcvZ5PW24I-0jnohcXzVLDkhIEGzwP1bIBM_xP0i7A_0I9ufZa583hlaDjPT_6uuh2A==&uniplatform=NZKPT&langua

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索牵引康复机器人零位标定与运动控制

关键词

索牵引；零位标定；迭代学习控制；

摘要

随着社会经济的发展,人们对康复治疗的追求日益提高,促使康复机器人迅速发展。康复机器人与索牵引技术的结合,简化了机器人结构、增强了柔顺性、且具有工作空间大以及人机交互安全等优点。本文通过对索牵引康复机器人的国内外发展现状与机器人零位标定技术和控制策略的研究,设计出一款用于下肢康复的索牵引康复机器人,对其进行零位标定分析与仿真控制分析,并设计实验对理论分析进行验证。主要研究工作如下:

基于人体尺寸标准与下肢正常步态轨迹,设计索牵引康复机器人的本体结构。根据绳索张紧条件推导机器人所需的绳索数量及其分布,确定索牵引康复机器人的构型。使用拉格朗日法建立机器人动力学模型并依据虚功原理推导索力求解方法,根据索力要求采用零空间法分析索牵引康复机器人力旋量封闭工作空间,进一步计算力可行工作空间。最后,以工作空间为目标采用改进的遗传算法对索牵引康复机器人进行构型优化。

为提高机器人运行精度,基于建模、测量、参数辨识、误差补偿的标定步骤对索牵引康复机器人进行零位误差标定。首先建立机器人零位误差模型；采用光学三维动作捕捉系统进行数据测量；运用 matlab 对测量数据进行计算获取零位参数；对比理论参数对索牵引康复机器人零位进行调整补偿。同时使用 matlab 对测量系统应用软件 Cortex 进行二次开发实现在线数据传输与零位参数辨识,并通过实验完成索牵引康复机器人的零位标定。

最后,针对非线性、强耦合、高重复性的索牵引康复机器人,提出了迭代学习的控制策略。首先介绍其基本理论,分析不同迭代学习律的收敛性。在零初始误差的前提下,对索牵引康复机器人分别进行了开闭环 D 型迭代学习控制仿真实验,并且分析不同的控制器参数对控制算法的影响。基于开环 D 型迭代学习控制对索牵引康复机器人进行轨迹跟踪实验,对比实验结果证明了迭代学习控制的可行性。

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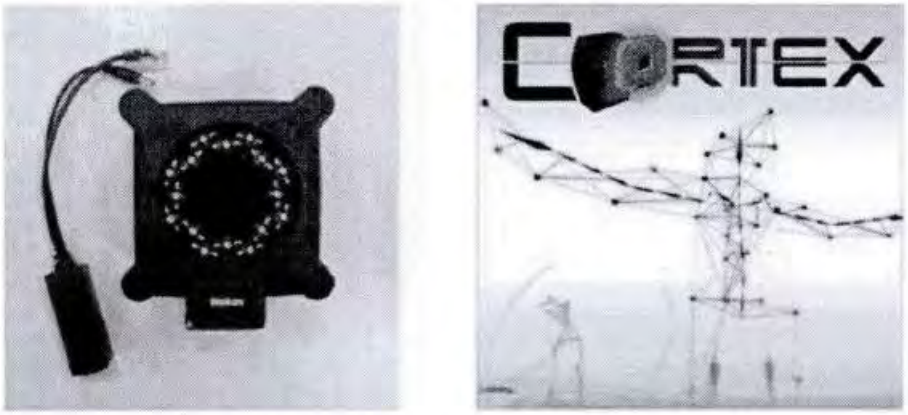

(a) 动作捕捉镜头 Mars2H　　(b) 分析处理软件 Cortex

图3.2 光学三维动作捕捉系统

NOKOV 度量动作捕捉在研究中的应用摘录

本文采用 Nokov 光学三维动作捕捉系统对索牵引康复机器人进行测量。系统采用十位灰阶深度加 GrayScale 图像处理算法的双优组合，可以进行非常精确的运动捕捉。每个镜头内置图像处理器，可以保证数据实时迅速传输。系统定位误差小于 0.08mm，精度为亚毫米级满足测量要求。整个系统包括动作捕捉镜头 Mars2H 与分析处理软件 Cortex 如图 3.2 所示。

Nokov 光学三维动作捕捉系统采用了被动式红外光原理设计，通过动作捕捉镜头发出的红外光照射到反光标志点 Marker 点上，来识别 Marker 点位置坐标。运用 Nokov 光学动作捕捉系统的捕捉原理，在索牵引康复机器人上关键点处固连 Marker 点来识别机器人各点位置信息。

Nokov 光学三维动作捕捉系统拥有独立的坐标系统，Cortex 分析处理软件所导出的 Marker 点位置坐标的参考坐标系为测量系统自身定义的全局坐标系，与索牵引康复机器人的世界坐标系不重合。因此，为了将测量数据应用于误差识别，需要将测量数据进行坐标系转换。

缠绕有满足长度要求的绳索，绳索一端固连在机器人实体模型上，机器人在四根绳索协调牵引下实现确定运动；测量系统部分主要由前文所述的 Nokov 光学三维动作捕捉系统组成，主要包括动作捕捉镜头 Mars 2 H 与分析处理软件 Cortex；控制系统部分由上位机与下位机组成，具体实现方式为 P C + 运动控制卡的控制模式［51］。索牵引康复机器人整体系统如图 3.5 所示。

引用格式 李浩.索牵引康复机器人零位标定与运动控制[D].西安电子科技大学，2020.DOI：10.27389/d.cnki.gxadu.2020.003464.

链接

https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CMFD&dbname=CMFD202201&filename=1021034184.nh&v=MDU4NThNMUZyQ1VSN2ImWU9ScEZ5N2hWNy9KVkYyNUg3TzdHdERFcTVFYlBJUjhlWDFMdXhZUzdEaDFUM3FUclc=

X. Agricultural Robot

A Dynamic Resistive Force Model for Designing Mobile Robot in Granular Media

Keywords

Contact modeling; filed robots; methods and tools for robot system design; wheeled robots;

Abstract

Locomotion failure is the challenge for wheeled robots applied in granular media, which puts a high demand on the design of wheels. Due to a lack of a mechanical analysis method that can analyze the dynamic interaction between wheel and granular media, it is a challenge to seek design guidance for the wheel geometry. To this end, we introduce a Dynamic Resistive Force Model (DRFM) method suitable for 3D dynamic intrusion. In this method, Granular Resistive Force Theory (RFT) can be extended to 3D RFT smoothly by using granular parameters, and additional velocity terms can describe the effect of intrusion velocity on intrusion force. The relationship between wheel geometry and mechanical properties can be established by performing differential processing on the wheel surface and integrating the force generated by each micro-surface. On this basis, a complete set of solutions is proposed for the design of mobile robot wheels in granular media, and the screw-propelled wheel is taken as an example to optimize it. Theories, simulations, and experiments have all proved that the optimized wheel can produce greater thrust and lift than normal screw-propelled wheel when ensuring the stability of smooth propulsion. The proposed solution and the optimized screw-propelled wheel bring insights for designing mobile robots in granular media.

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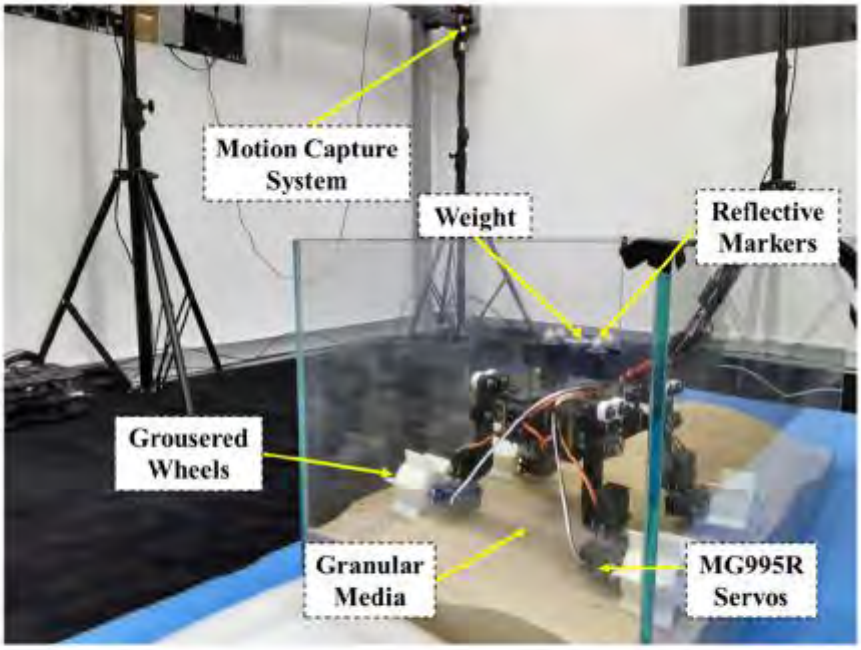

Fig. 1. **An overview of the robot motion experiment.** Robot equipped with grousered wheels is moving on sand media. The robot is driven by MG995R servos and its mass can be changed by weights. The motion data is captured by motion capture system through four reflective markers on the robot.

How NOKOV Contributes to the Research

Reflective markers were placed on the body of the robot, and kinematic data of the robot was captured by the NOKOV system. Eight NOKOV motion capture cameras were mounted around the bed, and the kinematic data were captured by reflective markers attached to the robot at a speed of 60 frames per second.

Citation Huang L, Zhu J, Yuan Y, et al. A dynamic resistive force model for designing mobile robot in granular media[J]. IEEE Robotics and Automation Letters, 2022, 7(2): 5357-5364.

Link https://ieeexplore.ieee.org/abstract/document/9729492

Design and evaluation of a robotic apple harvester using optimized picking patterns

Keywords

Robotic apple harvester; Motion capture; Apple detection; Apple detachment

Abstract

A robotic apple harvester consisting of a mobile platform, a manipulator, an end-effector, a stereo camera, and a host computer was constructed and evaluated using two picking motions. The field tests showed all apple picking with success rates of 80.17% and 82.93% when using anthropomorphic and "horizontal pull with bending" motions, respectively. The main reasons for picking failure were depth misalignment, detachment failure, and blocked grasp. The "horizontal pull with bending" and anthropomorphic motions took 1.14 s and 3.13 s, respectively. The full picking cycle process using "horizontal pull with bending" motion was 12.53 ± 0.53 s, 4.64 s less than the average picking time when using anthropomorphic picking motion (17.17 ± 0.36 s). The picking process using anthropomorphic motion experienced a lower dynamic payload, meaning less effort would be required by the manipulator joints; however, fruit slipping decreased the overall success rate. The "horizontal pull with bending" picking motion had a superior picking cycle time and success rate. Notably, there were no stem-pulled or bruised apples during picking process using either motion. Based on this study, both picking motions have the potential to be applied in harvesting robots.

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Fig. 8. NOKOV motion capture system.

How NOKOV Contributes to the Research

Through observing, it was found that workers widely adopt a picking motion that involves bending and pulling upwards. The NOKOV motion capture system (Beijing NOKOV Science & Technology Co., Ltd., China) was used to collect data on the movements of pickers' upper arms. As shown in Fig. 8, there were eight digital cameras with a 2048 × 1088 resolutions and ± 0.15 mm 3D accuracy positioned around the test area. Data were collected by tracking marked points and transferred to the host computer and processed in real-time to calculate the coordinates, velocity, and acceleration of the moving objects in space (Zhang et al., 2021b).

Citation Bu L, Chen C, Hu G, et al. Design and evaluation of a robotic apple harvester using optimized picking patterns[J]. Computers and Electronics in Agriculture, 2022, 198: 107092.

Link https://www.sciencedirect.com/science/article/abs/pii/S0168169922004094

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GY-SLAM: A Dense Semantic SLAM System for Plant Factory Transport Robots

Keywords

SLAM, YOLOv5, GhostNet, octree maps, grid maps, plant factory

Abstract

Simultaneous Localization and Mapping (SLAM), as one of the core technologies in intelligent robotics, has gained substantial attention in recent years. Addressing the limitations of SLAM systems in dynamic environments, this research proposes a system specifically designed for plant factory transportation environments, named GY-SLAM. GY-SLAM incorporates a lightweight target detection network, GY, based on YOLOv5, which utilizes GhostNet as the backbone network. This integration is further enhanced with CoordConv coordinate convolution, CARAFE up-sampling operators, and the SE attention mechanism, leading to simultaneous improvements in detection accuracy and model complexity reduction. While mAP@0.5 increased by 0.514% to 95.364, the model simultaneously reduced the number of parameters by 43.976%, computational cost by 46.488%, and model size by 41.752%. Additionally, the system constructs pure static octree maps and grid maps. Tests conducted on the TUM dataset and a proprietary dataset demonstrate that GY-SLAM significantly outperforms ORB-SLAM3 in dynamic scenarios in terms of system localization accuracy and robustness. It shows a remarkable 92.59% improvement in RMSE for Absolute Trajectory Error (ATE), along with a 93.11% improvement in RMSE for the translational drift of Relative Pose Error (RPE) and a 92.89% improvement in RMSE for the rotational drift of RPE. Compared to YOLOv5s, the GY model brings a 41.5944% improvement in detection speed and a 17.7975% increase in SLAM operation speed to the system, indicating strong competitiveness and real-time capabilities. These results validate the effectiveness of GY-SLAM in dynamic environments and provide substantial support for the automation of logistics tasks by robots in specific contexts.

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(a) Transfer robot platform (b) NOKOV motion capture system

Figure 4. Equipment for collecting the GY-SLAM dataset. **(a)** MR600 mobile robot, D455 camera, and reflective markers; **(b)** 12 NOKOV Mars 2H cameras and motion capture system.

Table 3. Equipment parameters for collecting the SLAM dataset.

Device	Parameter	Value
D455 Camera	Image Resolution FOV	640 × 480 at 30 FPS (OV9782) 86° × 57°
MR600 Robot	Overall Dimension Installation Heigh Elevation Angle Slow Speed Fast Speed	625 × 590 × 465 mm^3 350 mm 10° 0.4 m/s 0.8 m/s
NOKOV Mars 2H Cameras	Marker Camera Number 3D Accuracy	Φ15 mm × 10 12 ±0.15 mm

How NOKOV Contributes to the Research

We used the D455 camera to capture RGB and depth data and employed the NOKOV Motion Capture System to obtain real-time trajectory ground truth for the robot. The MR600 transport robot from ShiHe Company served as the mobile platform, with the D455 camera mounted on a bracket at the top of the robot. We incorporated the work elements that the transport robot faced into the dataset to validate the subsequent target detection network's ability to recognize targets and eliminate dynamic feature points. The dataset encompasses various scenarios, including handheld and wheeled robot shooting, fast and slow motions, as well as normal and multi-rotational scenarios. The equipment used for collecting the SLAM dataset is shown in Figure 4, with specific parameters provided in Table 3.

Citation Xie X, Qin Y, Zhang Z, et al. GY-SLAM: A Dense Semantic SLAM System for Plant Factory Transport Robots[J]. Sensors, 2024, 24(5): 1374.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001183007300001

Influence of track ground pressure distribution uniformity on traction under slope

Keywords

Barycentre adjustment, Traction adhesion, Stability, Driving on slopes

Abstract

Traction is one of the important parameters for measuring the operation of vehicles. When tracked vehicles are driven on slopes, gravity can cause an uneven distribution of ground pressure on both sides of the tracks, seriously affecting the traction adhesion of the vehicle. The purpose of this study is to study the influence of the uniformity of contact pressure distribution on traction force on track slopes with the intent to change the uniformity of the distribution of contact pressure on track slopes by adjusting the position of the vehicle's barycentre. To quantify the distribution phenomenon of track grounding pressure, a coefficient for predicting the uniformity of ground pressure distribution is proposed. Platform tests are conducted on slopes of 5°, 10°, 15°, and 20°, and the results showed that the higher the slope, the worse the uniformity of ground pressure distribution and traction. After adjusting the vehicle's barycentre, the uniformity of ground pressure distribution was improved. Whenever the uniformity of ground pressure distribution increased by 1 %, the vehicle's traction increased by \~3 %. On a 20° slope, the barycentre adjustment increased the uniformity of ground pressure distribution increases by 17.6 % and improved traction by 58.5 %. Therefore, barycentre-adjusted tracked vehicles can greatly improve the uniformity of ground pressure distribution, thereby improving slope traction adhesion and safety. The results and patterns of this study have great guiding significance for the design and performance evaluation of tracked vehicles in hilly and mountainous areas in the future.

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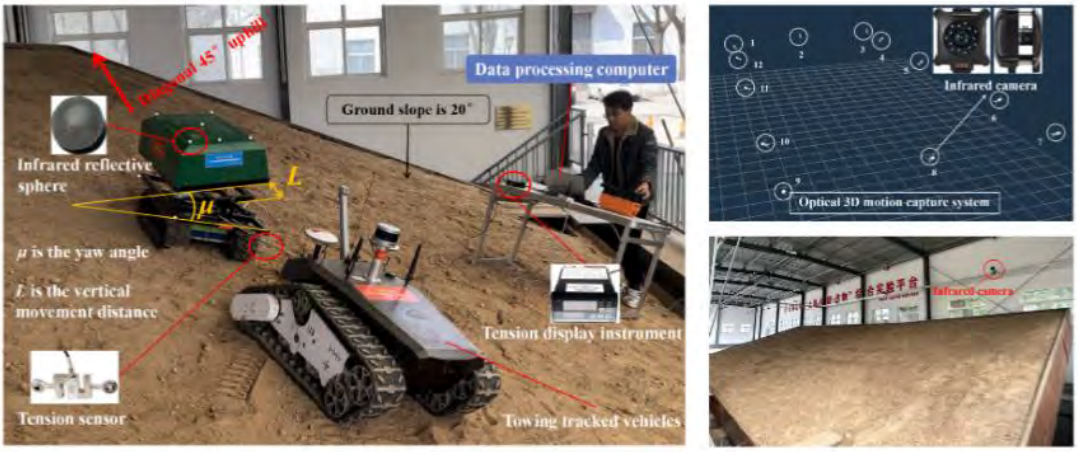

Fig. 4. Slope traction test (after barycentre adjustment).

How NOKOV Contributes to the Research

2.4.1. Platform testing and instruments
The traction test is conducted on the comprehensive "soil-machine-crop" test platform to simulate hilly and mountainous areas. Fig. 4 shows the traction test of the test vehicle when the platform slope is at 20°, and the vehicle being pulled in the traction test is also a remote-controlled electric tracked vehicle. The length × width × height of the vehicle is 1000 mm × 680 mm × 430 mm, the track gauge is 500 mm, the grounding length of the track is 900 mm, and the width of the track is 180 mm. The traction force is measured by a tension sensor with a capacity of 5 kN (Chino sensor ZNLBS, Bengbu, Anhui, China), with a measurement frequency of 1 Hz. The actual forward speed of the vehicle with barycentre adjustment was measured by an optical 3D motion capture system (NOKOV Mars4H, Beijing, China) with a recognition accuracy of 0.1 mm. The system consists of 12 infrared cameras, which are evenly distributed around the test platform in a circle. The maximum detection distance is 32 m, infrared cameras collect 4 MP, and the installation height of the camera is 3 m above the ground. By attaching an infrared reflective ball to the vehicle with barycentre adjustment, the vehicle's driving speed can be recorded in real time. The theoretical forward speed of the vehicle with barycentre adjustment is recorded by two Hall magnet induction speed sensors with a response frequency of 10 kHz installed on the driving wheels (YHDZ P4-56, Chino Sensor, Puyang, Henan, China).

Citation Mu X, Li Z, Ji Y, et al. Influence of track ground pressure distribution uniformity on traction under slope[J]. Biosystems Engineering, 2025, 257: 104252.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001548181400002

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Parameter identification algorithm for separated cable-driven parallel mechanisms via calibration error compensation

Keywords

Parameter identification, Cable-driven parallel robot, Least squares method, Beetle algorithm, Error compensation

Abstract

For traditional Cable-Driven Parallel Robot (CDPR), changing the workspace is relatively difficult and requires reconfiguring the anchor points and outer frame. The main reason is that the frame-type configuration is often difficult to unfold and the anchor points are hard to identify. Additionally, since the anchor points are not connected by a fixed structure, the parameters can only be determined through manual measurement, which has limited accuracy. Therefore, the position values of the anchor points should be re-identified using appropriate calibration methods, particularly through the use of rapid automatic calibration methods. This paper proposes a rapid identification and calibration-error compensation method for anchor points of a separated cable-driven parallel robot operating in a non-structured environment. By calibration-error compensation, we refer to the simultaneous estimation and correction of anchor-point positions and calibration-reference errors, which reduces bias from imperfect calibration hardware and enhances identification robustness. To improve the motion accuracy of the moving platform, a static motion error identification model is established based on kinematics, and a least squares method is employed to fit the model and calculate the kinematic parameter positions. Additionally, since calibration plates are used for calibration, random errors may occur. Therefore, a hybrid optimization framework combining AHDBO and the least squares method is further proposed to address the local optimality problem caused by multi-anchor point error coupling. Experimental results showed that after parameter identification and error compensation, the average anchor point identification error was 3.225 mm, and the motion platform position error was 2.20 mm. These results confirm that the proposed parameter identification and compensation methods can effectively improve deployment precision in separated CDPR.

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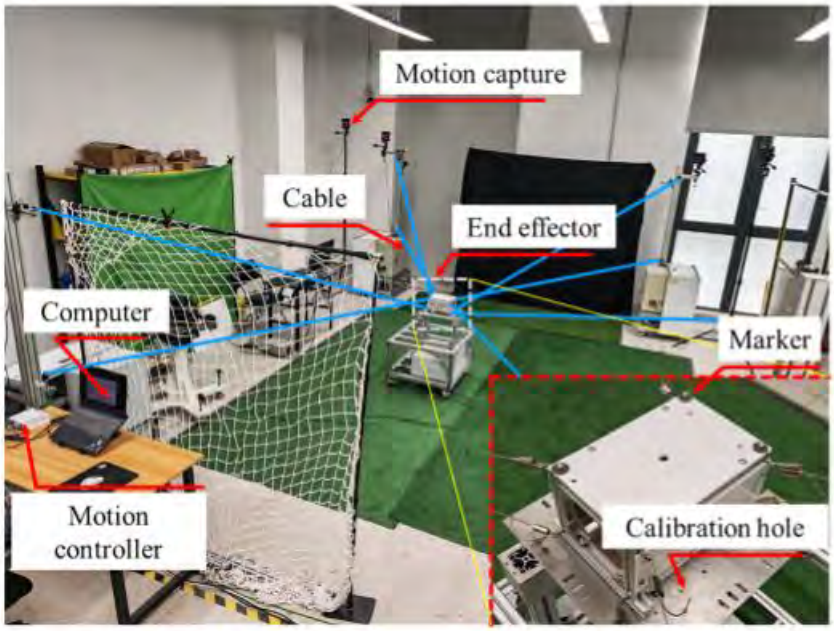

Fig. 7. Structural diagram of the CDPR.

How NOKOV Contributes to the Research

As shown in Fig. 7, multiple infrared reflective markers are arranged on the CDPR's motion platform, whose position is tracked using the NOKOV MARS-lH motion capture system. The system employs a single2-megapixel camera, with a maximum sampling frequency of 360 FPS and an output frequency of up to 150 FPS. The average measurement error is 0.158 mm, with a standard deviation of 0.071 mm, demonstrating the system's capability for high-precision dynamic tracking of the platform.

Citation Zhang Y, Zhang Y, Xian J, et al. Parameter identification algorithm for separated cable-driven parallel mechanisms via calibration error compensation[J]. Mechatronics, 2025, 112: 103421.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001605053000001

Performance Analysis and Experimental Validation of Small-Radius Slope Steering for Mountainous Crawler Tractors

Keywords

mountainous crawler tractors; slope steering; small-radius steering; ground contact pressure; soil-scraping resistance; amplitude-varied multi-peak cosine

Abstract

This study investigates the dynamic performance of mountainous crawler tractors during small-radius slope steering, providing theoretical support for power machinery design in hilly and mountainous regions. Addressing the mechanization demands in complex terrains and existing research gaps, a steering dynamics model is established. The model incorporates an amplitude-varied multi-peak cosine ground pressure distribution, employs position vectors and rotation matrices to characterize 3D pose variations in the tractor's center of mass, and integrates slope angle, soil parameters, vehicle geometry, center-of-mass shift, bulldozing resistance, and sinkage resistance via d'Alembert's principle. Numerical simulations using Maple 2024 analyzed variations in longitudinal offset of the instantaneous steering center, bilateral track traction forces, and bulldozing resistance with slope, speed, and acceleration. Variable-gradient steering tests on the "Soil-Machine-Crop" Comprehensive Experimental Platform demonstrated model accuracy, with <8% mean error and <12% maximum relative error between predicted and measured track forces. This research establishes a theoretical foundation for predicting, evaluating, and controlling the steering performance/stability of crawler tractors in complex slope conditions.

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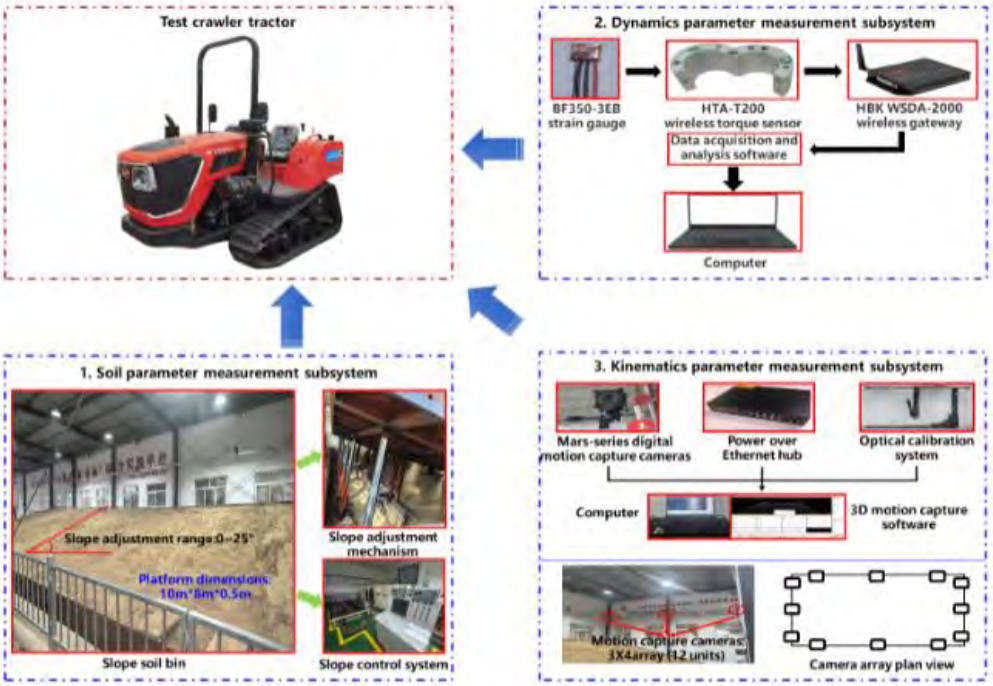

Figure 15. Slope small-radius steering measurement system for MCT.

How NOKOV Contributes to the Research

The kinematics parameter measurement subsystem was constructed using the NOKOV optical 3D motion capture system from Beijing Measure Technology Co.Ltd. (Beijing, China). It primarily acquires the following parameters during ve.hicle steering maneuvers: three-dimensional coordinates, azimuth angle, steering trajectory, displacement, linear velocity, linear acceleration, angular velocity, and angular acceleration.

Citation Duan L, Zhang L, Kang K, et al. Performance Analysis and Experimental Validation of Small-Radius Slope Steering for Mountainous Crawler Tractors[J]. Agronomy, 2025, 15(8): 1956.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001559551000001

Prediction Model for the Oscillation Trajectory of Trellised Tomatoes Based on ARIMA-EEMD-LSTM

Keywords

ARIMA-EEMD-LSTM algorithm; motion capture system; intrinsic mode function; oscillation trajectory prediction; tomato harvesting

Abstract

Second-order damping oscillation models are incapable of precisely predicting superimposed and multi-fruit collision-induced oscillations. In view of this problem, an ARIMA-EEMD-LSTM hybrid model for predicting the oscillation trajectories of trellised tomatoes was proposed in this study. First, the oscillation trajectories of trellised tomatoes under different picking forces were captured with the aid of the Nokov motion capture system, and then the collected oscillation trajectory datasets were then divided into training and test subsets. Afterwards, the ensemble empirical mode decomposition (EEMD) method was employed to decompose oscillation signals into multiple intrinsic mode function (IMF) components, of which different components were predicted by different models. Specifically, high-frequency components were predicted by the long short-term memory (LSTM) model while low-frequency components were predicted by the autoregressive integrated moving average (ARIMA) model. The final oscillation trajectory prediction model for trellised tomatoes was constructed by integrating these components. Finally, the constructed model was experimentally validated and applied to an analysis of single-fruit oscillations and multi-fruit oscillations (including collision oscillations and superposition oscillations). The following experimental results were yielded: Under single-fruit oscillation conditions, the prediction accuracy reached an RMSE of 0.1008–0.2429 mm, an MAE of 0.0751–0.1840 mm, and an MAPE of 0.01–0.06%. Under multi-fruit oscillation conditions, the prediction accuracy yielded an RMSE of 0.1521–0.6740 mm, an MAE of 0.1084–0.5323 mm, and an MAPE of 0.01–0.27%. The research results serve as a reference for the dynamic harvesting prediction of tomato-picking robots and contribute to improvement of harvesting efficiency and success rates.

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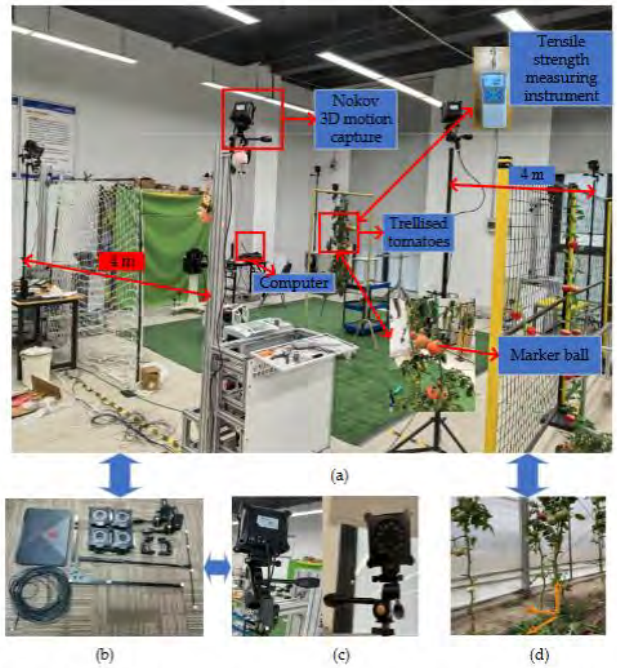

Figure 4. Oscillation trajectory acquisition system for trellised tomatoes. **(a)** Layout of the proposed oscillation trajectory acquisition system; **(b)** Nokov motion capture equipment; **(c)** Nokov motion capture cameras; **(d)** Establishment of the motion capture coordinate system.

How NOKOV Contributes to the Research

Abstract
Second-order damping oscillation models are incapable of precisely predicting superimposed and multi-fruit collision-induced oscillations. In view of this problem, an ARIMA-EEMD-LSTM hybrid model for predicting the oscillation trajectories of trellised tomatoes was proposed in this study. First, the oscillation trajectories of trellised tomatoes under different picking forces were captured with the aid of the Nokov motion capture system, and then the collected oscillation trajectory datasets were then divided into training and test subsets. Afterwards, the ensemble empirical mode decomposition (EEMD) method was employed to decompose oscillation signals into multiple intrinsic mode function (IMF) components, of which different components were predicted by different models.

Citation Wu Y, Zhang Y, Zhao P, et al. Prediction Model for the Oscillation Trajectory of Trellised Tomatoes Based on ARIMA-EEMD-LSTM[J]. Agriculture, 2025, 15(23): 2418.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001633916900001

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基于虚拟航道控制的多无人机覆盖喷灌算法

关键词

多无人机覆盖路径规划；虚拟航道；混合整数规划；模拟退火算法；农田全覆盖喷洒

摘要

调难以及多无人机覆盖路径规划的复杂度高的难题，设计了一种基于虚拟航道控制的多无人机区域覆盖喷灌算法。该算法规划多无人机虚拟覆盖航道，使得无人机仅需在预设航道内按照等间隔排布即可高效完成对农田的覆盖。该算法无需进行复杂得多机协同路径规划，从而显著简化了覆盖任务的实施。作为所提出算法的应用，针对特定农田区域采用一种分区方法将不规则农田分割成多个矩形的农田子区域。通过运用模拟退火算法求解无人机在不同子区域中的分配及航道规划的混合整数规化问题，提升灌溉效率。实验结果表明，该算法具有喷灌效率高、计算简便、规划速度快等特点，能够快速实现农田的全面覆盖喷洒，在多无人机自主喷洒农药方面具有广阔的应用前景。

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图 11　实机实验

NOKOV 度量动作捕捉在研究中的应用摘录

最后我们假定室内的一块 的规则矩形区域为需要进行喷洒作业的农田区域，由架 Tello TT 无人机和 NOKOV 室内动作捕捉系统来实验验证该算法。无人机的位置和姿态信息由 NOKOV 系统提供，二者通过同一局域网连接在一台主机电脑上。无人机的最大速度为，机间距离，覆盖完成时间共计 48s。由图 11 所示，两架无人机顺利地通过航道其路径经过的区域可以覆盖指定区域。该实验进一步证明了算法的有效性。

引用格式 李道文,杨鑫松,孙亚平,等.基于虚拟航道控制的多无人机覆盖喷灌算法[J].电子制作,2025,33(09):33-39.DOI:10.16589/j.cnki.cn11-3571/tn.2025.09.028.

链接
https://kns.cnki.net/kcms2/article/abstract?v=I7RSZimHV9NaET3yZ-f2D-wbIr6J4LE46fxkKYNasLY0jTuWRoQ2QPdcXfaumI9SaINnr_TF4XJhFf-Wme3berpSRMIDyn8r1gcaNn2v9gDoDkAmGHeXXQXuhSg2xP534F7HER-VzVjkXXP19093C1hSu7neyyn8gi4qJ0IQXQfE9qu7WNHSvg==&uniplatform=NZKPT&language=CHS

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基于旋转激光雷达的融合定位建图方法

关键词

旋转激光雷达；传感器融合；运动学模型；定位与建图；外参标定

摘要

激光雷达（Light Detect and Range，LiDAR）具有抗干扰能力强、测量距离远、测距精度高等优点，已经广泛应用于无人驾驶、机器人、地理测绘等领域。常用的激光雷达扫描线束和角度均有限，导致其扫描视场角（Field of View）较小且点云稀疏，不能保证可靠的帧间关联，因此难以满足可靠定位与精细化建图要求。通过额外旋转轴驱动激光雷达而形成的旋转激光雷达，可以显著提升扫描 FoV 和点云密度。然而，旋转激光雷达增加的旋转轴会引入新的结构外参，也会由于机械磨损、自身运动以及热胀冷缩等因素导致外参徐变，因此不仅需要高效精确地估计结构外参，也需要在定位建图的同时实现外参的自标定，以提高旋转激光雷达的融合定位建图性能。针对旋转激光雷达结构外参标定以及自标定定位建图问题，本文主要开展了以下研究工作：

（1）基于多线激光雷达、IMU（Inertial Measurement Unit）和电机（含编码器）搭建单自由度连续式旋转激光雷达系统，为后续工作构建了硬件基础。同时，针对当前旋转激光雷达运动学模型不完整问题，通过分析编码器特性分别构建激光雷达-编码器运动部分以及编码器静止部分-IMU 的两组外参关系，并结合电机转动与平台运动的补偿模型、IMU 全局状态，构建了旋转激光雷达系统的统一运动学模型，为后续工作奠定了理论基础。

（2）针对当前旋转激光雷达结构参数标定仍需要借助特定工具和规则标定场景等限制，通过多维曲率计算和归一化概率估计以设计网格区域 FG（Filtered Grid）策略，并结合基于 RANSAC（Random Sample Consensus）的多网格区域平面提取、粗细平面关联以及加权优化的 GRSC（Grid RANSAC）思路，提出了一种启发式的且不借助于特定标定工具和规则场景的结构参数标定方法 FGRSC，提升了对比方法平均 42.02%的标定精度。

（3）针对高动态属性旋转激光雷达的机械磨损、自身运动以及热胀冷缩等因素导致的外参徐变问题，通过将结构外参、传感器外参以及 IMU 状态封装到同一观测模型，并基于 ESIEKF（Error-state Iterated Extended Kalman Filter）优化框架，首次提出了一种面向旋转激光雷达的多外参自标定融合定位建图方法 OMC-SLIO（Online Multiple Calibration Spinning LiDAR Inertial Odometry），实现了结构外参、传感器外参、全局位姿的同时优化以及地图更新。

（4）基于提出的 FGRSC 与 OMC-SLIO 方法，利用旋转激光雷达分别构建了静态建图设备和动态定位建图设备，并将其分别应用于粮食自动化扦样机器人系统以及复杂场景实时定位建图，验证了本文研究工作的实际应用价值。

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图 4-3 Nokov 运动捕捉系统实验室

NOKOV 度量动作捕捉在研究中的应用摘录

实验室场景的 Nokov 运动捕捉系统可以提供旋转激光雷达系统平台实时运动的精确位姿信息，由于定位与建图相辅相成，因此通过连续位姿路径的对比，不仅可以精确地定量评价各个对比方法的定位性能，也可以间接评价其建图性能。
本章进行了两组对比实验，其中一组对比实验在实验室内使用 Nokov 运动捕捉系统的精确定位结果作为真值，如图 4-3 所示。

引用格式 汪双.基于旋转激光雷达的融合定位建图方法[D].西南科技大学，2024.DOI：10.27415/d.cnki.gxngc.2024.000043.

链接
https://kns.cnki.net/kcms2/article/abstract?v=DFdco8SIy0LvmnK8MaFHNKNR-lgezMazkDIsipq9gFqyJ7OPUp4LxqE3_Ex3QlybKOI3TZe3xDqTb77W5vWb7JXIILI9rZXB9ySzfFZyJh-zGhYIMhxPQQ==&uniplatform=NZKPT&language=gb

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结构化果园苹果收获机器人关键技术研究

关键词

苹果收获机器人；有限元分析；采摘机理；路径规划；深度学习

摘要

苹果收获具有劳动力需求大、劳动强度高、季节特征明显的特点，研发苹果收获机器人对水果产业自动化、智能化升级，应对日益显现的老龄化趋势具有积极意义。目前，苹果收获机器人的各主要部分的研究具有相对独立性的特点，并且苹果的识别定位和苹果收获机器人的姿态控制等问题都制约了苹果收获机器人的作业效果。因此，本文以苹果收获机器人为研究对象，围绕苹果收获机器人采摘姿态优化展开研究，涉及末端执行器与果实的交互作用、深度学习与果实识别和机械臂控制方面的功能实现和试验验证。论文的主要研究内容和取得的结论包括:（1）建立了枝条-果柄-果实的有限元模型，为末端执行器的抓握和损伤评估以及采摘动作优化提供理论依据。基于横观各向异性材料本构模型建立枝条和果柄模型，通过试验得到枝条轴向弹性模量(Ebz)、枝条径向弹性模量(Ebr)、果柄轴向弹性模量(Esz)和果柄径向弹性模量(Esr)分别为 181.69±17.88MPa、29.81±4.02MPa、106.42±13.30MPa 和 10.34±3.59MPa；枝条和果柄的异性平面弯剪模量分别为 337.05±66.52MPa(Grb)和 46.90±11.62MPa(Grs)。通过本构关系，令枝条和果柄的同性面泊松比(μXY)为 0.4，得到枝条(GbXY)和果柄(GsXY)轴向扭转剪切模量的估算值分别为 10.65MPa 和 3.70MPa；枝条(μbr)和果柄(μsr)的异性面泊松比的估算值分别为 0.20 和 0.11。基于内聚力模型对枝条和果柄之间的分离层进行了建模。分离层的最大牵引力(Ti，max)、最大牵引位移（δm）和断裂能释放率 Gic 分别为 5.01±0.68MPa，0.29±0.04mm 和 0.71±0.04kJ/m2。通过 Abaqus 软件对枝条-果柄模型有限元仿真结果和试验结果的对比表明，所建立的有限元模型可以对枝条-果柄连接的断裂过程做出预测。（2）分析了不同采摘方式对果实分离的影响。通过水平拉、垂直拉、弯转和扭转四种基本采摘动作的采摘试验，对果实分离载荷以及果实-果柄-果实的形状特征对采摘效果的影响进行了讨论。在采摘过程中，拉力，包括水平拉力和垂直拉力，是造成果实分离的主要因素。使果实分离所需切向力明显小于所需的法向力。果柄与枝条垂直的状态下，垂直拉力可能导致果柄拔出。果柄较长的果实需要较大的位移和角度来破坏枝条-果柄连接，增加了采摘失败的风险。基于建立的枝条-果柄-果实有限元模型对水平速度、垂直速度、弯转角速度和扭转角速度设计了四因素三水平仿真试验，通过方差分析和响应面分析，讨论了各因素对果实分离力的显著性影响，并对参数进行了优化，结果表明，水平横拉、弯转和扭转的组合为的最佳采摘动作，可以为苹果采摘机器人机械臂路径规划提供参考。（3）基于有限元法分析了柔性三指 FRE 结构的末端执行器的抓握能力以及评估对果实损伤的可能性。通过方差分析和响应面分析，讨论了软指材料硬度、果实质心到手掌距离和果实大小对拉力的显著性影响，并对参数进行了优化。结果表明 TPU 硬度、水果质心到水果距离以及果实尺寸是影响末端执行器

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抓握能力的显著性因素；以最大拉力为优化指标，确定 TPU 硬度为 90HA，果实质心到手掌距离为 65mm；试验结果与预测结果相符，两者相关系数 R2=0.8221。通过果肉的拉伸和压缩试验建立苹果果肉的损伤塑性模型。在抓握过程损伤评估仿真试验中，果皮 Mises 应力最大为 0.159MPa，果肉最大应力为 0.082MPa，接触压力最大为 4.178N；验证试验中，薄膜压力传感器安装在仿真试验接触力最大位置，最大接触力为 4.572N。最大接触力仿真值与实际最大接触力的误差为 8.62%。仿真与验证试验均表明该柔性三指末端执行器可以实现苹果的无损抓取。（4）基于人手动作捕捉数据和采摘动作优化仿真试验提出两种采摘动作，在 ROS 中使用 Moveit 进行路径规划，通过仿真和试验验证其可行性。使用 NOKOV 动作捕捉系统采集人摘苹果时的上臂动作，通过路径规划使机器人能够"拟人化"采摘。针对 XARM5Lite 在 MoveIt 中完成建模和规划组的配置；选用开源运动规划库中的 RRTConnect 算法对拟人动作和"横拉-弯"动作路径规划进行了的仿真与测试，结果表明基于 MoveIt 的机械臂路径规划可以实现预期目标。（5）研发的苹果收获机器人集成视觉系统、控制系统、末端执行器和机械臂等模块，实现自动采摘功能，实验室和果园试验表明苹果收获机器人具有较高的可靠性。果园试验结果表明苹果收获机器人的总成功率为 81.60%，其中拟人动作的采摘方法的收获成功率为 80.17%，采用"横拉-弯"采摘动作收获方法的成功率为 82.93%。造成采摘失败的原因为深度失准，分离失败和抓握受阻。"横拉-弯"采摘动作和拟人采摘动作的果实平均最大分离力分别为 10.12N 和 8.63N。拟人采摘动作的末端动态载荷较小，使机械臂的整体负载降低，但由于果实的滑移降低了采摘成功率；"横拉-弯"的采摘动作的时间较短，收获成功率较高。两种采摘动作都没有导致果柄拔出或果肉损伤。两种采摘方法都显示出应用于收获机器人的潜力。

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基于上述研究内容，本研究的技术路线如图 1-7所示。

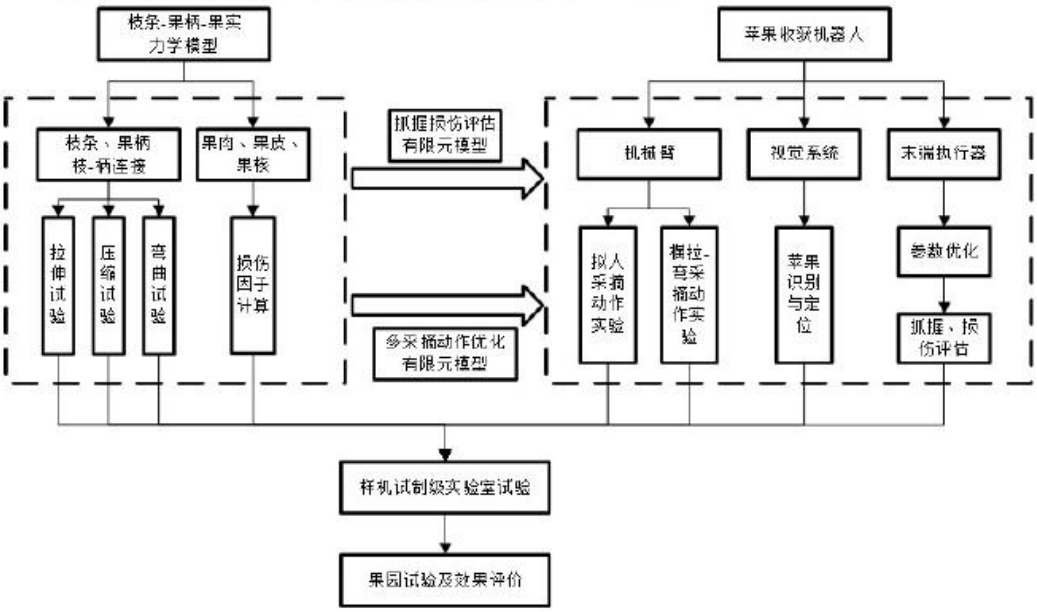

图1-7 总体技术路线图

Fig. 1-7 The overall technology roadmap of the research

NOKOV 度量动作捕捉在研究中的应用摘录

基于 NOKOV 动作捕捉系统采集人上臂的采摘轨迹，用于机械臂的路径规划。

引用格式 卜令昕.结构化果园苹果收获机器人关键技术研究[D].西北农林科技大学，2021.DOI：10.27409/d.cnki.gxbnu.2021.000038.

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温室双电机分布式驱动履带拖拉机设计与试验

关键词

电动履带拖拉机;双电机分布式驱动;温室农业;

摘要

针对现有小型电动动力机械驱动性能不足、转向性能较弱，较难满足温室作业空间狭小的生产需求等问题，设计了一种温室双电机分布式驱动履带拖拉机。基于质心位置分配法确定电动履带拖拉机质心理论位置，对各部件位置进行优化使质心实际位置接近理论位置，以得到质心最佳位置方案。以犁耕和运输作业为目标进行电动履带拖拉机电驱系统核心部件匹配，完成了电动履带拖拉机电控系统设计，并对试制的电动履带拖拉机进行基本性能试验和犁耕工况试验。结果表明：在直线行驶中，平均百米跑偏量为 1.259 m,单边制动最小转向圆半径平均值为 1 096 mm,单边制动最小通过圆半径平均值为 1 232 mm,原地转向最小转向圆半径平均值为 729 mm,电动履带拖拉机直线行驶性能和转向性能较好；当行驶速度为 1、3、5、7 km/h 时，拖拉机牵引功率分别达 1 367.1、4 201.1、6 922.8、9 173.3 W,最小平均牵引力为 5 320.4 N,远大于相近功率的燃油拖拉机和双电机分布驱动轮式拖拉机牵引力，可满足温室种植作业需求；在犁耕试验中，平均耕深 17.18 cm,平均耕幅 40.55 cm,续航时间 3.35 h,电动履带拖拉机动力性能和续航性能良好。双电机分布式驱动履带拖拉机可满足温室多种作业农艺需求，可为温室新能源动力机械研发提供依据。

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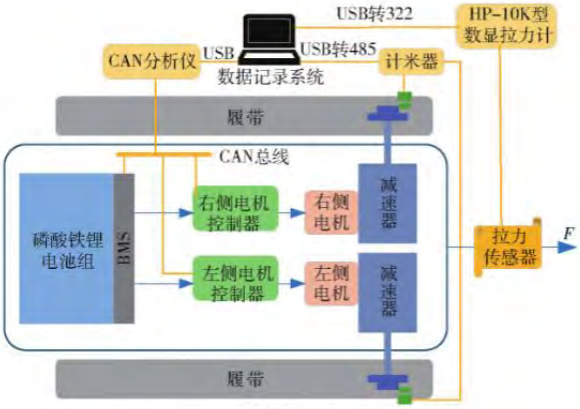

(a) 结构框图

(b) 实物图

图 6　试验数据采集与记录系统

Fig. 6　Test data acquisition and recording system

1. 数据记录系统　2. 牵引负载　3. 拉力传感器　4. CAN 分析仪
5. 数显拉力计　6. 遥控器　7. 计米器

NOKOV 度量动作捕捉在研究中的应用摘录

3 试验
3.1 基本性能试验 3.1.1 直线行驶性能试验
在西北农林科技大学丘陵山地"土壤-机器-作物"综合实验平台,采用 Mars 4H 型 NOKOV 度量光学三维动作捕捉系统,对电动履带拖拉机进行直线行驶性能试验,如图 7 所示。
拖拉机行驶速度为 2km/h,土壤含水率平均值为 15.2%,土壤坚实度平均值为 742.8 kPa。试验结果如图 8 所示,电动履带拖拉机最大跑偏量为 1.765 m,平均跑偏量为 1.259 m,远小于国家标准(GB/T 15370.4-2012)\[28],表明电动履带拖拉机直线行驶性能较好。

引用格式 郭惠萍,王霆伟,谢广杰,等.温室双电机分布式驱动履带拖拉机设计与试验[J].农业机械学报,2025,56(09):780-788.

链接
https://kns.cnki.net/kcms2/article/abstract?v=yqBhao7Q9gxdRj8OZDEhDQXVGOkYsOvdwLkOY7_AaINGTx7B-B3ElnYiMkFsEsVCbMYaPkkoxMlwWyg4iht4GMhJ8xCoZJ9z2MpccBhvi1Ve2umH5nOYBjGwP27_6CUN6Z0uNUlHUnZD4u6LJX8YZ-D5ekU9dYAVHP8aixbJWdFBf_iw6SwPNg==&uniplatform=NZKPT&language=CHS

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自然场景下成熟柑橘果实分类识别与定位方法研究

关键词

柑橘采摘机器人；RGB-D 相机；YOLO v3；分类识别；三维空间定位

摘要

成熟果实收获作为果实生产作业的首要任务之一，研发一款智能采摘机器人有利于缩短采摘时间、降低采摘成本、减小人工劳动强度，与此同时，对于促进我国农业由机械化向高度自动化和智能化迈进有着重要的现实意义。本文以课题组自行研发的柑橘采摘机器人作为试验平台，旨在通过研究自然场景下成熟柑橘果实的分类识别与定位方法，使其具有自主感知和收获能力，以此提升采摘机器人的智能化程度。主要研究内容如下：1)基于 RGB-D 相机的视觉系统搭建与样本采集。分析对比了现有的三种采用不同原理的深度相机，结合课题实际要求，综合考虑了双目立体视觉、结构光以及飞行时间的优劣势，最终选择了基于 TOF 原理的 Kinect v2 深度相机，并对其进行视场角和深度误差等进行了分析，获取相机最佳工作距离保证视觉系统的精度和稳定性的同时，综合相机最佳工作距离与柑橘采摘机器人的采摘距离确定了采集样本的拍摄距离范围，在此距离范围内通过在不同时间段采集不同光照角度下的柑橘图像，以保证训练样本具有良好的泛化性。2)成熟柑橘果实分类识别模型构建及改进。结合采摘机器人的实际采摘需求，根据果实的生长分布情况及遮挡关系对果实进行了不同类型的划分，在此基础上制作了单果无遮挡、单果树叶遮挡、单果树枝遮挡、单果枝叶混合遮挡以及重叠无遮挡、重叠树叶遮挡、重叠树枝遮挡以及重叠枝叶混合遮挡 8 种类型的柑橘训练数据集，与此同时，构建了以 Darknet53 为特征提取网络的 YOLO v3 分类识别模型，通过对模型预测边框的输出进行分析，基于分析结果对识别模型的网络结构进行了相应的改进，增加了网络的输出和改进网络的损失函数，试验结果表明：改进后的模型对于不同类型的柑橘果实平均识别准确率达 86.42%，相较于改进前的 82.56%提升了 3.86%，检测速度从改进前的 26.37fps 提升到 30.23fps。3)不同类型柑橘果实三维空间定位。通过改进后的识别模型对不同遮挡状态的柑橘果实进行分类识别，利用彩色图像与深度图像之间的映射关系完成彩色图像和深度图像的配准，在此基础上，根据相机像素坐标系与世界坐标系之间的转换关系获取柑橘果实采摘点的三维坐标信息以及果实的横径和纵径，完成对不同类型柑橘的三维空间定位。试验结果表明：在 x 轴方向上的平均定位误差为 2.51mm、在 y 轴方向上的平均定位误差为 2.71mm、在 z 轴方向上的平均定位误差为 3.35 mm，在机器人工作范围内柑橘横径测量的平均误差为 2.43mm，纵径测量的平均误差为 2.41mm，满足机器人的实际采摘需求。4)柑橘采摘机器人果实目标分类识别与定位系统开发及应用。在 Linux 系统下以 Qt5.10 作为软件编译平台，在 Opencv4.0 图像处理库中对相关识别与定位算法进行了集成，完成了视觉系统的开发和软件界面的设计，实现了柑橘采摘机器人视觉系统的界面式的操作，利用搭载该系统的柑橘采摘机器人在户外进行了多组采摘试验，以验证该系统的实用性和稳定性。

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图 4.9 Nokov 光学三维运动捕捉系统

表 4.1 Nokov 光学三维运动捕捉系统 硬件参数

型号	分辨率	像素数	频率	延迟	视场角	HELD 数量	镜头
Mars 2H	2048×1088	2.2MP	340HZ	2.8ms	56.3°×43.7°	16	8mm

NOKOV 度量动作捕捉在研究中的应用摘录

为了准确获取本文方法对于果实定位精度，在实验室环境下利用如图 4.9 所示的北京度量科技公司生产的 Nokov 光学三维运动捕捉系统对空间任意位置的果实进行了定位精度测试。该套设备的具体参数如表 4.1 所示。实验过程如图 4.10 所示，将 Kinect 相机固定在可升降的支架上，在相机彩色镜头和深度镜头范围内任意位置悬挂一个柑橘果实,首先通过 Nokov 光学三维运动捕捉系统分别捕捉柑橘果实及相机在其坐标系下的空间位置，然后通过本文方法获取柑橘果实在相机坐标系下的空间位置，最后通过对比 Nokov 光学三维运动捕捉系统坐标系下得到的相机与柑橘果实的相对位置与本文方法得到的相机与柑橘果实的相对位置来评价本文方法的定位精度。

引用格式 熊龙烨.自然场景下成熟柑橘果实分类识别与定位方法研究[D].重庆理工大学，2020.DOI：10.27753/d.cnki.gcqgx.2020.000645.

链接

https://kns.cnki.net/kcms2/article/abstract?v=3uoqlhG8C475KOm_zrgu4lQARvep2SAkHr3ADhkADnVu66WViDP_3NCaYTOCM9juqvAdEZvVhefImY1JJKS9LWJ5jlarXpcY&uniplatform=NZKPT

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XI. Others

3D-MOF-Lattice Inspired Programmable Metamaterials Based on Reconfigurable Polyhedral Origami

Abstract

Metamaterials have attracted significant attention due to their unconventional mechanical properties. However, a major limitation of conventional metamaterials lies in the fixed and uniform microstructures, limiting their ability to realize diverse functionalities. Inspired by the network chemistry of the 3D architectures of metal–organic frameworks (MOFs) crystal networks, a reconfigurable design strategy based on polyhedral origami patterns is proposed. Leveraging intrinsic bifurcation behavior, a set of modular units with tunable stiffness and adjustable Poisson's ratios is developed. Both experimental and theoretical investigations confirm that these modules exhibit diverse mechanical responses, including quasi-zero, positive stiffness, bistability, and a continuously tunable Poisson's ratio spanning negative to positive values. By assembling modules in desirable modes, a programmable metamaterial network with customizable mechanical performance is presented. This approach provides a versatile platform for designing multifunctional mechanical metamaterials and offers practical value in applications such as advanced shock-absorbing systems, enhancing versatility and adaptability.

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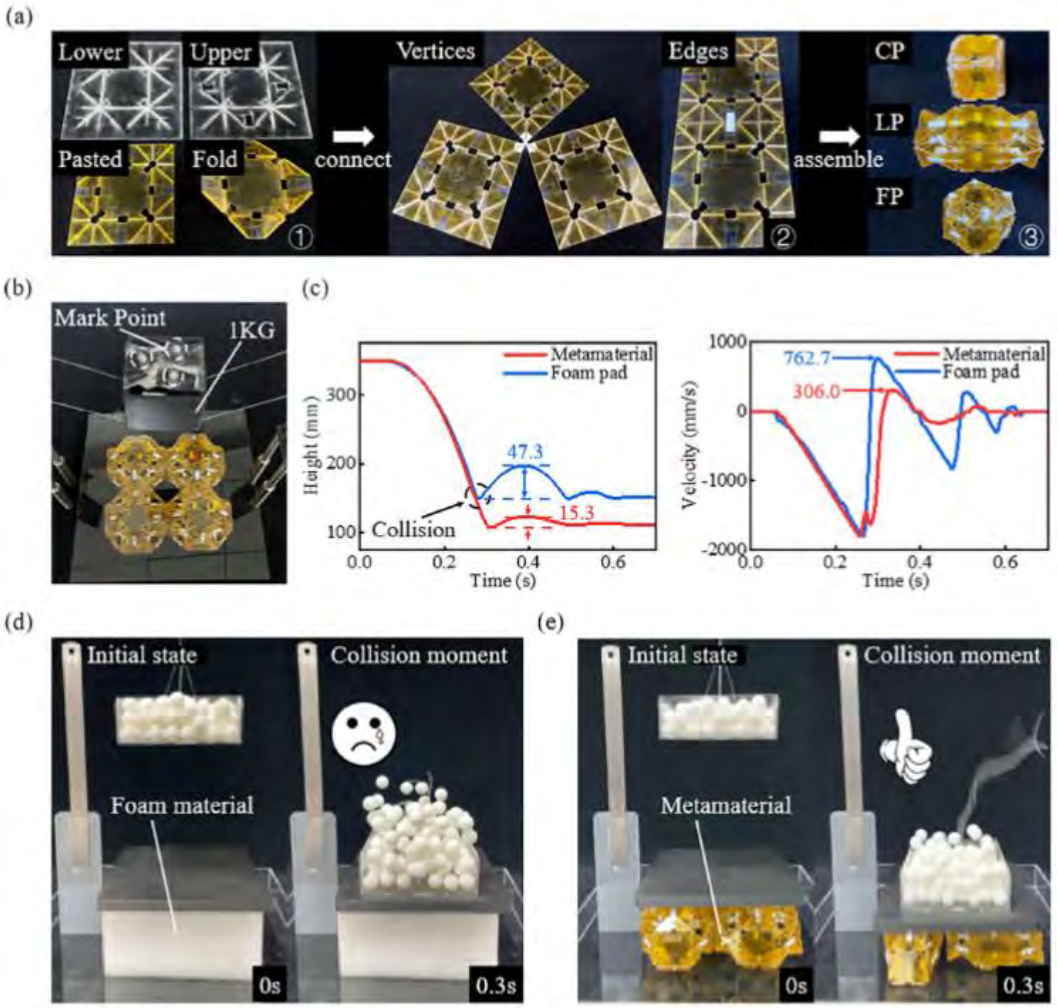

Figure 6. Experimental Comparison of Metamaterial Shock Absorption Performance. a) Manufacturing process of the metamaterial module. b,c) 1 kg weight drop impact test. d,e) Ball shock absorption experiment.

How NOKOV Contributes to the Research

Experimental Setup: Single axis loading test was conducted using a material mechanics testing machine (model: BT2-FA010TH. A50.002) with a loading rate of 0.01 mm s−1 and a loading end condition of 10N. Using a motion capture system (Nokov optical 3D motion capture system with measurement error less than 0.01 mm) to measure the lateral and longitudinal displacement, velocity, and acceleration of various surfaces of metamaterials.

Citation Kang X, Zhang Y, Fan H, et al. 3D-MOF-Lattice Inspired Programmable Metamaterials Based on Reconfigurable Polyhedral Origami[J]. Advanced Science, 2025: e17921.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001637552500001

A Global Optimal and Outlier-Robust Point Set Registration Method

Keywords

Branch-and-bound (BnB) algorithm, robust global optimization, simultaneous pose and correspondence registration, space target tracking

Abstract

Point set registration is an essential technique in the field of machine vision. In this article, we propose a robust global optimal solution to for the point set registration of feature points extracted from visual images, used in remote (300 – 120 km) space target tracking and targeting tasks. Specifically, we begin with cases where correspondences among point sets are known, establishing a cost function centered on maximizing the consensus set, wherein rotational and translational parameters are determined using voting methods and the branch-and-bound (BnB) algorithm, respectively. We then adapt this foundation to tackle the more challenging scenario of unknown correspondences in simultaneous pose and correspondence registration by adjusting the cost function and BnB bounding functions, supplemented with nested iterations to accurately determine rotation and translation parameters. Finally, the comprehensive experimental comparisons executed across synthetic and real datasets, along with ground-based spacecraft pose measurement setup, illustrate that, compared to existing methods, our proposed approach achieves precise estimations under the influence of noise and outliers. Moreover, compared to the globally nested BnB scheme, our method reduces computational complexity and enhances solution speeds.

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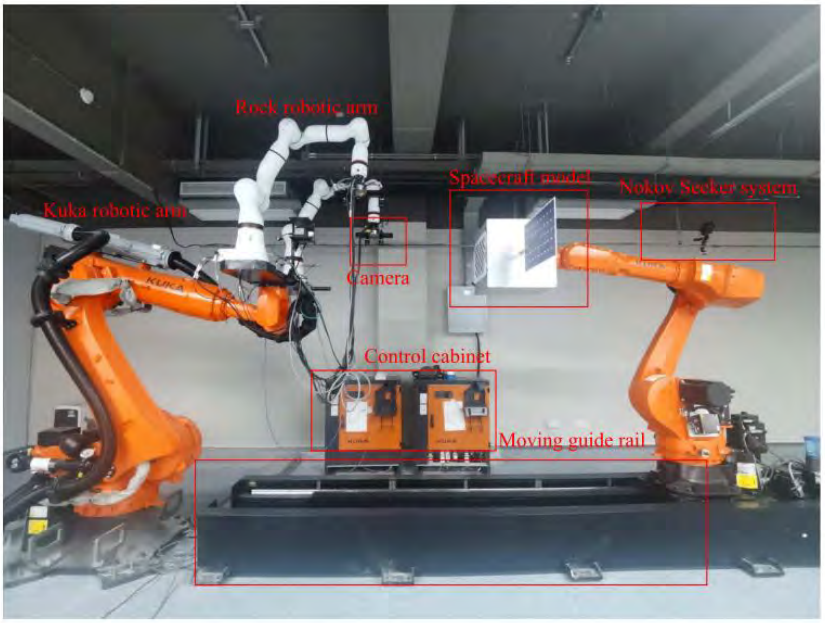

Fig. 14. On-site experimental setup to capture the spacecraft pose.

How NOKOV Contributes to the Research

The setup is enhanced by the inclusion of eight infrared cameras positioned around the ceiling, forming a comprehensive motion capture system (NokovSeeker). Concurrent with these actions, data acquisition was conducted using theNOKOVcalibration framework in conjunction with a monocular camera for comprehensive capture.

Citation Long C, Hu Q, Guo P, et al. A Global Optimal and Outlier-Robust Point Set Registration Method[J]. IEEE Transactions on Industrial Informatics, 2025.

Link https://ieeexplore.ieee.org/abstract/document/10847584

A LiDAR-Camera Calibration and Sensor Fusion Method with Edge Effect Elimination

Keywords

Point cloud compression, Surface reconstruction, Strips, Laser radar, Image color analysis, Shape, Sensor fusion

Abstract

This article presents a multi-sensor calibration and fusion work for a dense reconstruction and colorization system. Unlike previous research, it explicitly addresses the edge effect in LiDAR measurements in both calibration and sensor fusion. The proposed calibration method can accomplish LiDAR-motor and LiDAR-camera calibration at a one-time experiment. The feature extraction algorithm for the point cloud automatically eliminates the edge-effect-induced noises in the calibration process. The experiment results show that it can achieve even better results than work without edge effect elimination in terms of calibration errors. As a result, it has achieved a calibration accuracy superior to previous researches. The system is testified by an indoor scene, which shows a desirable color point cloud generation with dense and clean data.

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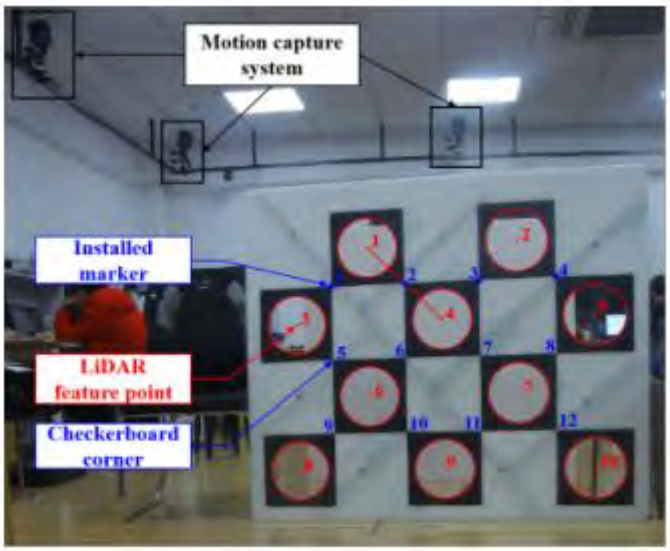

Fig. 4. The calibration experiment setup

How NOKOV Contributes to the Research

Instead, we attach markers on the corner points and use a motion capture system Nokov Mars4H to measure their positions in space as references. The accuracy of the motion capture system is ±0.1 mm. When we place the calibration board at different places, there is a distance between the positions of the same corner point.

Citation Lin Y, Fei Y, Gao Y, et al. A LiDAR-camera calibration and sensor fusion method with edge effect elimination[C]//2022 17th International Conference on Control, Automation, Robotics and Vision (ICARCV). IEEE, 2022: 28-34.

Link https://ieeexplore.ieee.org/abstract/document/10004361

A Method for Identifying Knee Joint Stiffness During Human Standing

Keywords

Standing, Joint stiffness, Three-stage inverted pendulum model, Lagrange's equation

Abstract

During human-robot interaction, the robot should react according to the change in the human body state. The stiffness is one of the important information. It is closely related to the stability and comfort in human movement. At present, the auxiliary equipment for standing does not consider the change of human joint stiffness. Therefore, this paper proposes a method that can identify the stiffness of the knee joint during human standing. Firstly, the human body structure is simplified to a three-section inverted pendulum model. The kinetic analysis is performed using Lagrange's equation. Then the expression of joint stiffness is solved by joint torque. The angles and angular velocities of the joints of the lower limbs of the human body during standing are measured experimentally. The errors in the measurements are modified by geometric relationships. The stiffness of the human body during standing is derived by substituting them into the derived expressions. The result shows that the method can identify the stiffness of the human knee joint during standing.

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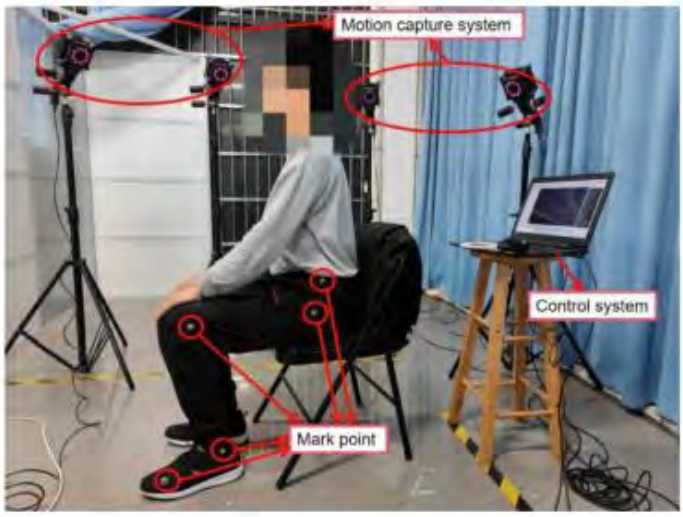

Fig. 2. The experimental scene, including a motion capture system, marker points and control system.

How NOKOV Contributes to the Research

In this section, the joint angles and joint angular velocities required to calculate the stiffness are measured. The measurement equipment uses an optical 3D motion capture system from NOKOV, The system consists of 8 infrared high-speed cameras. And itcan measure the displacement of marker points and the angle of their connecting lines.Figure 2 shows the experimental scene.

Citation Cheng G, Huang Y, Zhang X. A Method for Identifying Knee Joint Stiffness During Human Standing[C]//International Conference on Intelligent Robotics and Applications. Singapore: Springer Nature Singapore, 2023: 3-9.

Link https://link.springer.com/chapter/10.1007/978-981-99-6483-3_1

A Minimalist Self-Localization Approach for Swarm Robots Based on Active Beacon in Indoor Environments

Keywords

swarm robots; visual localization; optical beacon; self-localization; indoor environment

Abstract

When performing indoor tasks, miniature swarm robots are suffered from their small size, poor on-board computing power, and electromagnetic shielding of buildings, which means that some traditional localization methods, such as global positioning system (GPS), simultaneous localization and mapping (SLAM), and ultra-wideband (UWB), cannot be employed. In this paper, a minimalist indoor self-localization approach for swarm robots is proposed based on active optical beacons. A robotic navigator is introduced into a swarm of robots to provide locally localization services by actively projecting a customized optical beacon on the indoor ceiling, which contains the origin and the reference direction of localization coordinates. The swarm robots observe the optical beacon on the ceiling via a bottom-up-view monocular camera, and extract the beacon information on-board to localize their positions and headings. The uniqueness of this strategy is that it uses the flat, smooth, and well-reflective ceiling in the indoor environment as a ubiquitous plane for displaying the optical beacon; meanwhile, the bottom-up view of swarm robots is not easily blocked. Real robotic experiments are conducted to validate and analyze the localization performance of the proposed minimalist self-localization approach. The results show that our approach is feasible and effective, and can meet the needs of swarm robots to coordinate their motion. Specifically, for the stationary robots, the average position error and heading error are 2.41 cm and 1.44°; when the robots are moving, the average position error and heading error are less than 2.40 cm and 2.66°.

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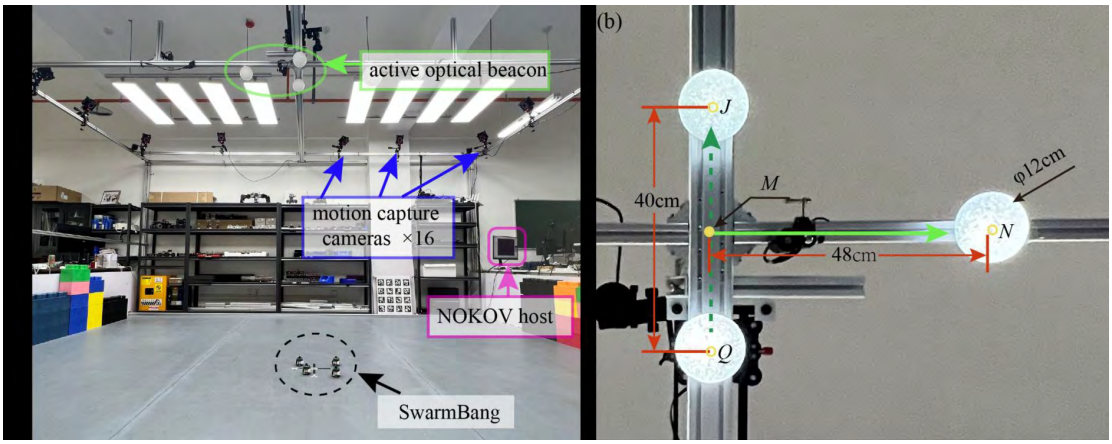

How NOKOV Contributes to the Research

In As depicted in Figure 6a, our experiments are conducted in a ~30 m2 indoor arena with flat ground and no obstacles. Around the arena, 16 NOKOV motion capture cameras are mounted, which connect to a host. This motion capture system serves to monitor the real-time position and heading of each SwarmBang robot. The NOKOV system has a positioning and orientation accuracy of 0.2 mm and 0.28°, respectively, so these collected data can be treated as the true pose to check the robot's self-localization results.

Citation Duan, M.; Lei, X.; Duan, Z.; Zheng, Z. A Minimalist Self-Localization Approach for Swarm Robots Based on Active Beacon in Indoor Environments. Sensors 2023, 23, 4926. https://doi.org/10.3390/s23104926

Link https://www.mdpi.com/1424-8220/23/10/4926

A Moving Object Detection Method for Mobile Robots Using Feature Point Sticky Tree

Keywords

moving object detection, feature points, sticky tree, moving camera

Abstract

Moving object detection is a common task for mobile robots when working in dynamic environments. Due to the nonstatic nature of the mobile robots themselves, we need to conduct the motion detection work under the moving camera assumption. Feature-point-based object detection is an important research direction to solve this problem. The distances and motion conditions of the feature points in both 2D image space and 3D physical space are critical criteria to cluster the points to objects. However, previous work never fully considered all the criteria and explored their complex relationship with object segmentation outputs. As a result, accurate segmentation can not be achieved when the differentiation condition only presents in part of the criteria space. Therefore, we proposed a novel feature point stickiness method to include all the above considerations. A fuzzy neural network is designed to assess the stickiness between any feature points, e.g., the possibility of being on the same object. The network is trained with small data set to capture the complex nonlinear relationship between the point distance and motions and the stickiness. In addition, a sticky tree growth algorithm is used to connect the feature points according to their stickiness distributions. The formation of the trees autonomously completes the object segmentation task. The method is testified in various experimental situations, including some challenging scenarios. It improved the object recall rate and precision rate to a large extent compared to previous works and showed high potential in providing precise trajectories of moving objects in the robot's workspace.

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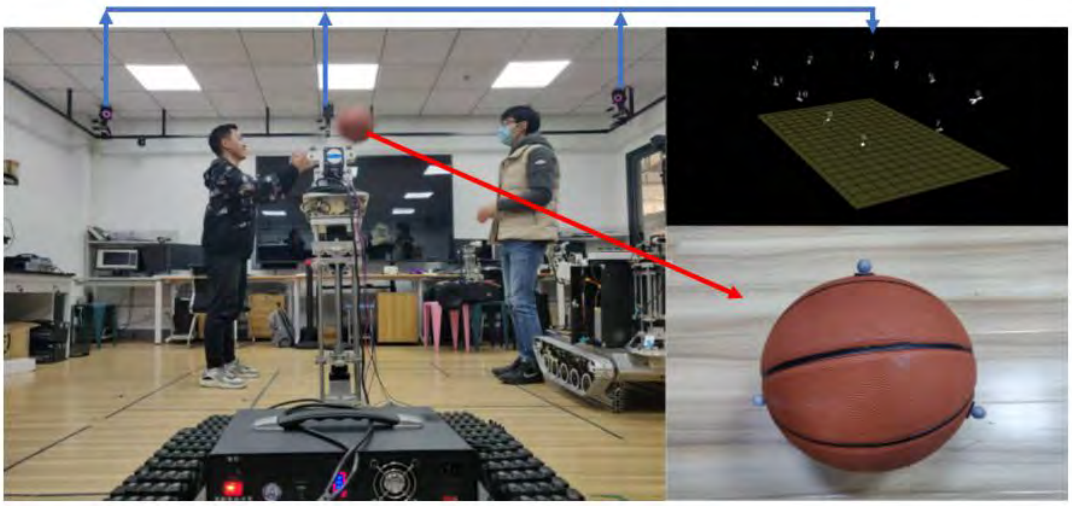

Figure 13: 3D motion tracking experiment

How NOKOV Contributes to the Research

Though it is not the focus of this paper, we present the rough estimation of the 3D trajectory measurement capability of the proposed 3D moving object detection algorithm in this subsection. The experimental system is set up in the laboratory, as shown in Fig.13. The detection object is chosen as the ball since it is the most manageable object to be measured by the motion capture system and with a relatively long trajectory in a short time. We attached markers on the ball and used a motion capture system Nokov Mars4H to measure its positions in real-time. The accuracy of the motion capture system is ± 0.1 mm, and its measurement is considered the ground truth for the ball's trajectory.

Citation Luo J, Zhou S, Zhu J, et al. A Moving Object Detection Method for Mobile Robots Using Feature Point Sticky Tree[J]. Available at SSRN 3994131.

Link https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3994131

A Robot 3C Assembly Skill Learning Method by Intuitive Human Assembly Demonstration

Abstract

With the development of the Internet and computer technology, the demand for 3C products such as mobile phones has surged. At the same time, due to the continuous improvement of labor costs, it is urgent to automate the 3C assembly lines with industrial robots. The motivation of this paper is to propose an efficient off-line programming by demonstration method to automate 3C assembly lines. This process consists of two phases. In the first phase, the optical motion capture device is used to capture the position and orientation information of human hands during assembly process. In the second phase, those information of a couple of demonstrations are learned to derive a robot control policy. To do so, the local outlier factor based anomalous point detection algorithm as well as the trajectory segmentation algorithm inspired by density-based spatial clustering is utilized in advance to pre- process the demonstration data. Then the human assembly skill represented by a probabilistic policy is learned from those data to drive the robot to accomplish the same assembly task under new environment. The Gaussian Mixture Model is utilized to pre-structure the policy. The offline programming by demonstration method efficiently transfers human experience to the robot. Experimental results demonstrate the effectiveness of the method.

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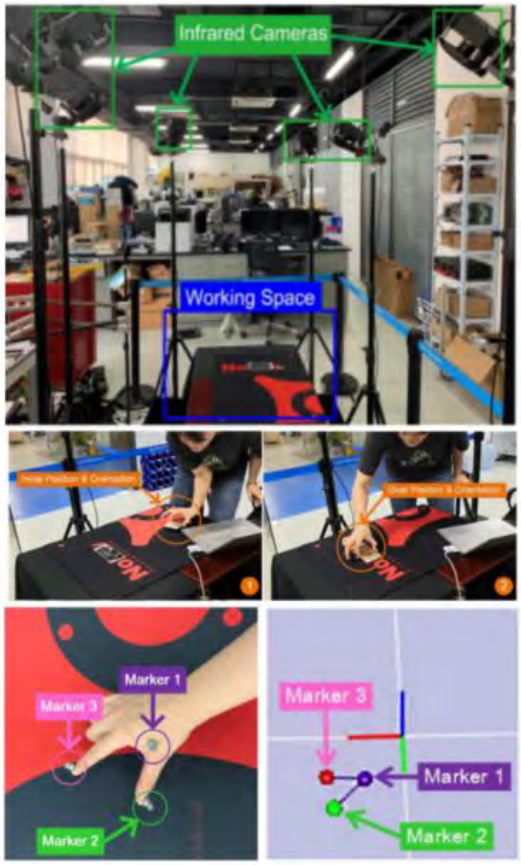

How NOKOV Contributes to the Research

For the purpose of acquiring human demonstration data the optical motion capture platform from NOKOV Science and Technology Cooperation Ltd. \[15], as shown in Fig.3, is selected to record the movement of reflective markers pasted on one hand of the operator at a 340fps sampling frequency. By doing so, the sub-millimeter positions of the operator's hand as well as fingers are recorded through the infrared cameras when the operator executes the assembly process. In view of the quickness and complexity characteristics of the 3C assembly process, Better still, the optical motion capture platform does not interfere the normal assembly work of the operator. In addition, the optical motion capture platform is capable of working in normal industrial environments with- out too much space usage and dense equipment distribution. Afterwards, by a series of data pre-processing techniques, several smooth assembly motion trajectories are obtained from multiple human assembly demonstrations. Finally, a policy for the robot to regenerate assembly motion trajectory that can achieve the same assembly task under strange start and goal positions and orientation is derived by the policy learning algorithm.

Citation Cao Z, Hu H, Yang X, et al. A robot 3C assembly skill learning method by intuitive human assembly demonstration[C]//2019 WRC Symposium on Advanced Robotics and Automation (WRC SARA). IEEE, 2019: 13-18.

Link https://ieeexplore.ieee.org/abstract/document/8931930

A Robot Programming by Demonstration Method for Precise Manipulation in 3C Assembly

Abstract

Industrial robots have been widely used in various production line but not in the 3C assembly line which is characterized by highly frequent change-over and still relies on labor heavily. To deal with this challenge, the Programming by Demonstration (PbD) method, which provides a simple and intuitive way for workers to transfer skills to the robot, will greatly reduces professional knowledge requirements for robot users. However, some practical factors in 3C assembly line, such as the mechanical diversities between the human body and the robot, make it difficult to apply PbD methods. Motivated by that, with a subtly designed demonstration data extraction platform and a posture mapping strategy, this article proposes a PbD method that transforms human assembly skill to the robot for 3C assembly tasks. Furthermore, by an iterative optimization method, the demonstration path is simplified to boost the assembly efficiency which counts for much in practice. A simulation and a 3C assembly experiment has demonstrated the effectiveness of the proposed method.

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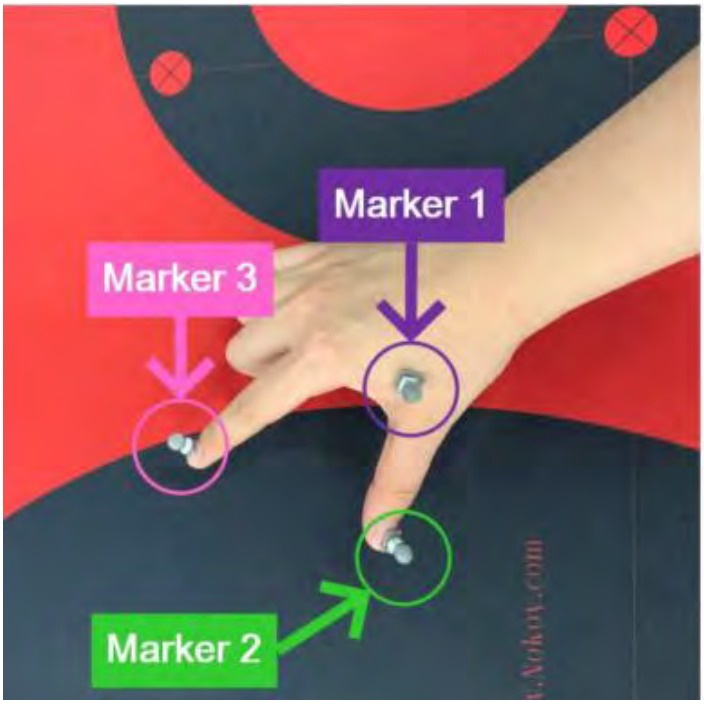

How NOKOV Contributes to the Research

A programming by demonstration (PbD) platform to trans- fer human 3C assembly skills to robots is proposed in this work, which consists of a demonstration data extraction platform (Fig. 3) and a robot assembly platform (Fig. 4). The demonstration data used in this work is obtained by an optical motion capture platform provided by Nokov Science & Technology Co., Ltd. \[13] that tracks three reflective markers pasted on the operator's hand, as shown in Fig. 6. By doing so, intuitive human assembly actions are obtained in a natural and convenient way that sets no threshold for non-expert operators. Details of the demonstration process can be found in the supplemented video. Furthermore, the robot assembly platform is facilitated with a 3D structure light camera to estimate the initial position and orientation of the components and an Universal Robot 5kg (UR5) robot to carry out the assembly task. However, owing to the inevitable mechanical diversity between human hand and robot's end- effector, several physically different grippers coupled with quick-change mechanism are designed for a couple of 3C components. With the quick-change mechanism, the UR5 robot is capable of selecting the grippers automatically.

Citation Zhao Z, Hu H, Yang X, et al. A robot programming by demonstration method for precise manipulation in 3C assembly[C]//2019 WRC Symposium on Advanced Robotics and Automation (WRC SARA). IEEE, 2019: 172-177.

Link https://ieeexplore.ieee.org/abstract/document/8931947

Accurate integrated position measurement system for mobile applications in GPS-denied coal mine

Keywords

Inertial navigation system; Multi-sensor fusion; Roadheader positioning; Underground coal mine; Unscented Kalman filter

Abstract

The automatic positioning of underground mobile applications plays a crucial role in enabling intelligent coal mining. However, due to the diverse kinematics and dynamics of these applications, various positioning methods have been proposed to match different targets. Nonetheless, the accuracy and applicability of these methods still fall short of meeting the requirements for field applications. Based on the vibration characteristics of underground mobile devices, a multi-sensor fusion positioning system is developed to enhance the accuracy of positioning in long and narrow global positioning system denied (GPS-denied) underground coal mine roadways. The system combines inertial navigation (INS), odometer, and ultra wide band (UWB) technologies through extended Kalman filter (EKF) and unscented Kalman filter (UKF). This approach enables accurate positioning by recognizing target carrier vibrations and facilitating fast conversion between multi-sensor fusion modes. The proposed system is tested on both a small unmanned mine vehicle (UMV) and a large roadheader, demonstrating that UKF enhances stability for roadheaders with strong nonlinear vibrations while EKF is more suitable for flexible UMVs. Detailed results confirm that the proposed system achieves an accuracy level of 0.15 m, meeting most coal mine application requirements.

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How NOKOV Contributes to the Research

To investigate the positioning characteristics of the two different scenarios, we arrange the proposed positioning system on UMV and road header separately. The inertial sensor is FOG IMU300 (Fog sins Technology Co., Ltd.), the UWB sensor is the LinkTrack P module (Noopoop Technology Co., Ltd.), and the absolute odometer is CAS38R12E06R4B (Shanghai Qiyi Electrical & Mechanical Equipment Co., Ltd.). The three-dimensional piezoelectric vibration sensor is 1A314E (DONGHUA Test Technology Co., Ltd.), and the infrared motion capture camera is Mars 2H (Beijing NOKOV Science & Technology Co., Ltd.). The sensors are arranged as Fig. 7 and the parameters are presented in Table 1.

Citation Accurate integrated position measurement system for mobile applications in GPS-denied coal mine

Link https://www.sciencedirect.com/science/article/pii/S0019057823001830

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Achieving Reliable Underground Positioning With Visible Light

Keywords

Location algorithm; personnel positioning; underground positioning; visible light communication (VLC); visible light positioning (VLP);

Abstract

Visible light technology shows great potential in the underground mine positioning today. Most visible light-based underground positioning technology deploy the receiver, such as photodiodes (PDs), on the mine tunnel ground and consider the miner's lamp on the ceiling as the transmitter. This incurs the unreliable reception of visible light signals and the difficult implementation of VLP systems due to the complex underground mine environment, such as the receiver being obscured or trampled by objects (e.g., Minecarts and Ore). We present a reliable underground positioning algorithm with visible light considering the actual mine environment. The key innovation is that we design a novel reverse mechanism, i.e., utilizing the existing miner's headlamp as the transmitter for broadcasting the specific light beacon representing the mine's identity information, and the PDs deployed on the ceiling of the mine tunnel as the receiver for optical signal reception. We can infer the current locations of all miners using a series of base stations constructed by PDs. If some special mine environment limits the large-scale deployment of base stations and causes the positioning blind spots, the inertial navigation is combined to achieve all miners' real-time positioning. We overcome some technical challenges for this new mechanism and the underground mine environment, such as optimal frequency selection, robust frequency identification, and accurate base station positioning. We conduct extensive experiments on our algorithm in a simulated mine tunnel, and the experimental results verify that our algorithm exhibits good performance.

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Fig. 21. Experimental scene.

How NOKOV Contributes to the Research

Motion Capture System: We use the motion capture system as the reference measurement system to obtain the real location of participants. The NOKOV motion capture system that we used consists of four optical motion capture lenses and some reflective markers. The optical motion capture lens (MASR1.3H) has an FOV of 56.3° × 43.7° and a sampling frequency of 240 Hz, and the reflective markers are reflective balls coated with special fluorescent materials. This motion capture system can achieve subcentimeter-level indoor positioning accuracy in an area of 12 m × 12 m. During the experiment, we deploy the reflective marker on the modulated LED light; hence, the position of the reflective marker determined by the motion capture system is taken as the real location of participants.

Citation Pang M, Shen G, Yang X, et al. Achieving reliable underground positioning with visible light[J]. IEEE Transactions on Instrumentation and Measurement, 2022, 71: 1-15.

Link https://ieeexplore.ieee.org/abstract/document/9740565

Adaptive Head Pose Estimation with Real-Time Structured Light

Keywords

Head Pose Estimation, Structured Light, 3D Reconstruction

Abstract

Head pose estimation (HPE) is a crucial task in pose recognition, but the existing HPE methods suffer from low robustness, low accuracy and inconvenience of contact measurement. In this paper, we build up an infrared structured light system for head pose estimation and propose an adaptive head pose estimation method to improve robustness and accuracy without the need for training. Firstly, we utilize a dynamic structured light system to acquire both the standard model and real-time dynamic data. Then, an iterative registration algorithm is proposed to adaptively segment the facial region which remains stable excluding distractions such as expressions and estimate the head pose. We experimentally evaluate the effectiveness of our method under conventional and large-angular head motion, and different expressions. The results demonstrate our method achieves highly accurate and robust real-time head pose estimation in a contactless manner.

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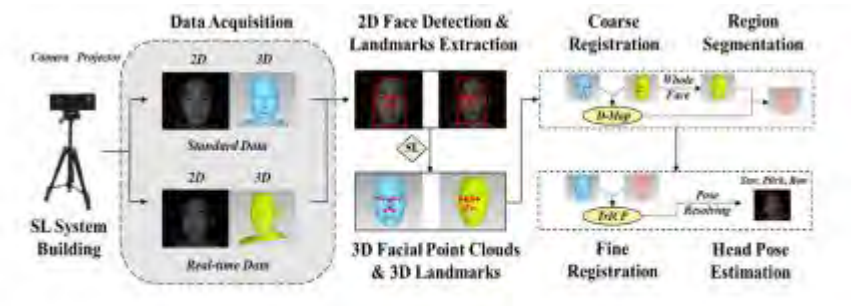

Fig.1. The workflow of our method.

How NOKOV Contributes to the Research

The infrared SL system we built consists of an infrared camera (FLIR BFS-U3-04S2M, with aresolution of 720\540 pixels and maximum frame rate up to 522 Hz and equipped with an infrared filter), a DLP projector (TI-DLP4500, with aresolution of 912\1140 and the maximum frame rate up to 4225 Hz, infrared light source with a wavelength of 850 nm). In addition, we used the NOKOV optical 3D motion capture system to obtain the ground truth of the head poses.

Citation Wang Y, Ye Y, Gu F, et al. Adaptive Head Pose Estimation with Real-Time Structured Light[C]//ICASSP 2024-2024 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP). IEEE, 2024: 3485-3489.

Link https://ieeexplore.ieee.org/abstract/document/10446561

Analysis of coiling and deployment of a bistable composite boom with a penetration-free contact simulation procedure

Abstract

Bistable deployable composite booms (bi-DCB) made of carbon fiber reinforcement polymer (CFRP) are widely utilized as supporting and driving components in deployable space membrane structures. This paper presents a simulation procedure for the coiling and deployment process of the bi-DCB based on the absolute nodal coordinate formulation. Before the deployment analysis is performed, a quasi-static analysis is performed to establish the stable coiled configuration of the bi-DCB. A novel penetration-free contact simulation method is introduced, which comprises a penetration check module and adjustment modules for coordinate updates during each Newton – Raphson iteration. This method effectively simulates both boom-to-boom and boom-to-roller contact. CFRP bi-DCBs are fabricated, and experiments utilizing a motion capture system are carried out to validate the simulation results pertaining to the coiling and deployment processes. The findings indicate that the proposed approach agrees well with the experimental results, both in terms of stable coiled configuration and deployment trajectory. A noticeable deviation in deployment speed is observed between simulation and experimental results, with the difference primarily attributed to multiple damping mechanisms including viscous damping, friction, and air resistance.

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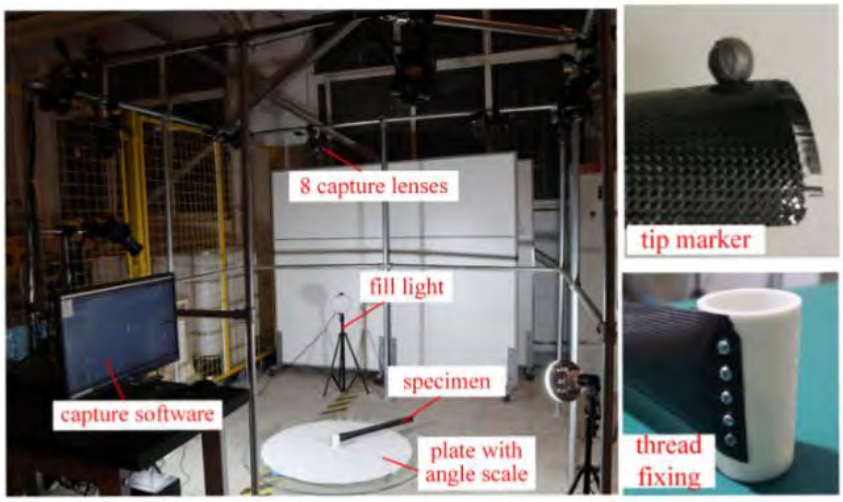

Fig. 16 Trajectory of the boom tip based on the NOKOV Motion Capture System

How NOKOV Contributes to the Research

The deployment experiment is conducted to validate the simulation procedure. One end of the boom is affixed to the roller using screws, as shown in Fig.16. The boom uncoils from its initial configuration, as shown in Fig.14. A marker is attached to the free tip, and its position is tracked using a motion capture system"NOKOV Motion Capture System" that comprises eight infrared motion capture lenses, as shown in Fig.16.

Citation Wang, Tengfei, Yangdong Du, and Yakun Zhao. "Analysis of coiling and deployment of a bistable composite boom with a penetration-free contact simulation procedure: T. Wang et al." Acta Mechanica (2025): 1-18.

Link https://webofscience.clarivate.cn/wos/alldb/full-record/WOS:001492115300001

Angular-velocity-free prescribed performance attitude control for spacecrafts based on high-order fully actuated system approach

Keywords

Spacecraft attitude control. HOFA system approach, Prescribed performance control, Extended state observer, Semi-physical experiment

Abstract

This paper investigates the prescribed performance attitude control of spacecraft with inertia uncertainties, external disturbances, and unknown angular velocity. Firstly, the system model of spacecraft attitude is formulated based on Modified Rodrigues Parameters (MRPs). This model is then reformulated into a high-order fully actuated (HOFA) model via state transformation and prescribed performance functions. The inertial uncertainties, external disturbances, and unknown angular velocity are treated as lumped disturbances, compensated by an extended state observer (ESO). A novel controller based on the HOFA system approach is proposed, guaranteeing that the attitude errors remain within prescribed-performance bounds. The stability of the closed-loop system is proved via the Lyapunov method. Numerical simulations and a semi-physical experiment verify the effectiveness of the proposed controller, demonstrating its adaptability to space mission requirements and practical feasibility.

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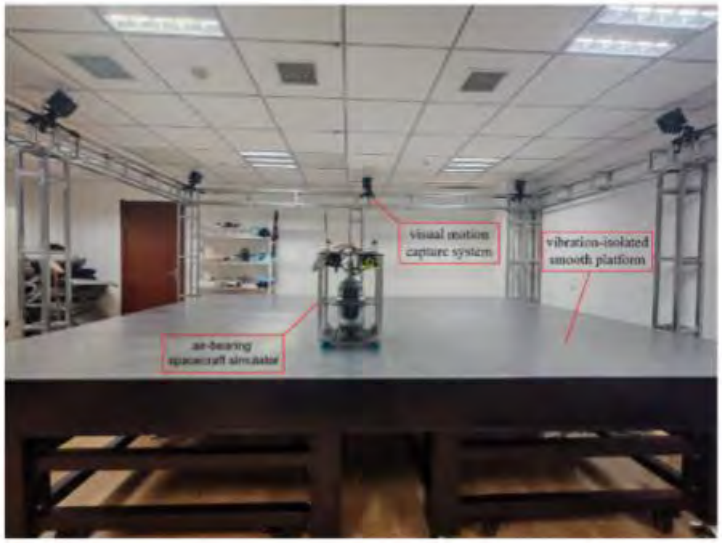

Fig. 4. The ground-based air-bearing microgravity simulation experimental platform.

How NOKOV Contributes to the Research

The air-bearing platform in Fig. 4 consists of a vibration-isolated smooth platform (2.8 × 3.6 m, surface smoothness 0.8 μm, flatness 0.05 mm/m²), a visual motion capture system (NOKOV Mars2H, positioning accuracy better than 0.15 mm, latency 2.4 ms), and an air-bearing spacecraft simulator. Fig. 5 presents the air-bearing spacecraft simulator, comprising a Microprogrammed Control Unit (MCU), six rotor propulsion systems, marker balls, four air-bearing feet, and a gas cylinder.

Citation Lin Z, Feng S, Zhang J, et al. Angular-velocity-free prescribed performance attitude control for spacecrafts based on high-order fully actuated system approach[J]. Control Engineering Practice, 2026, 167: 106651.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001628403800002

Application of Dynamic Weight Particle Swarm Optimization with Cross Factor in Joint Calibration

Keywords

Heuristic algorithms, Motion segmentation, Dynamics, Particle measurements, Motion measurement, Particle swarm optimization, Optimization

Abstract

The alignment of inertial measurement units(IMUs) to segment is an important step in inertial motion capture, which directly affects whether the imu data can fully represent the motion of the segment. Inspired by the gene crossover and mutation of Genetic Algorithm(GA), we propose a dynamic inertial weighted particle swarm optimization algorithm with cross factor to solve the joint constraint problem, and compared our algorithm with Particle Swarm Optimization(PSO) and Dynamic Inertial Weighted Particle Swarm Optimization(DPSO) algorithms to show the superiority of our algorithm during human lower limb movements. The experiment shows that introduced the random cross mechanism between particles with larger fitness and only the effective cross retained, makes the new algorithm show better search ability and convergence effect in this project, the stability and effectiveness are also improved. Our current work provides a good support for accurate calculation of joint angles in the future.

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(a) (b)

Fig. 3. Overview of the motion capture test equipment

How NOKOV Contributes to the Research

The Xsens Dot is set to collect data at a sampling frequency of 120 Hz. The Nokov infrared optical motion capture system (Beijing, China) was used to obtain high precision knee angles as reference values.Alignment between IMU and segment is accomplished through the joint constraint model to complete the IMU-based joint angle estimation. The obtained joint angle is used as the observed value and the joint angle obtained through Nokov is used as the reference value to calculate the RMSE, the results are shown in Fig.5. The RMSE ranges were from 1.62 to 2.94 for 3DOF joint angle.

Citation Jiang C, Wang W, Yang D W, et al. Application of Dynamic Weight Particle Swarm Optimization with Cross Factor in Joint Calibration[C]//2022 6th International Conference on Communication and Information Systems (ICCIS). IEEE, 2022: 159-163.

Link https://ieeexplore.ieee.org/document/9998132

Arbitrary Spatial Trajectory Reconstruction based on A Single Inertial Sensor

Abstract

Compared with visible, infrared rays, and ultrasonic positioning technologies, the signal acquisition of portable inertial sensors is not affected by the external environment, such as light and occlusion. Therefore, motion tracking based on inertial signals is a promising complement. However, accurate trajectory reconstruction based on inertial sensors is a great challenge due to intrinsic and measurement errors, especially the drift error that exacerbates the accumulative error in trajectory calculation. To address this challenge, we propose a new trajectory reconstruction method, geometric dynamic segmental reconstruction (GDSR), where we treat the movement trajectory as a combination of basic trajectories. To this end, we design a temporal and spatial interaction segmentation approach to decompose the trajectory into basic segments by combining the dynamic feature of inertial measurement unit (IMU) signals with the spatial morphological feature of motion. Accordingly, we design a geometrical model library with undetermined parameters to match these segments. For precise parameter prediction, we propose an extra-supervised learning method that integrates different prediction tasks into one framework, which can not only expand training samples, but also enable different subtasks to compete with each other, thus improving the parameter prediction accuracy of each subtask, thereby accurately approximating the trajectory segments. To quantify the trajectory reconstruction accuracy, we propose the Fréchet spline sliding error (FSSE) and length error ratio (LER) to evaluate curve similarity. The range of FSSE is \[0, 2], where 0 means that the two curves have the same shape. The range of LER is \[1, +∞], where 1 means that the two curves have the same length. We test different IMUs in two experimental scenarios and one public available dataset. In all three tests, the FSSE of the GDSR method is less than 0.09, and the LER is less than 1.31, which is significantly better than all the comparison methods.

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Fig. 11. Scene of motion collection within the optical camera facility (the left panel), and the racket attached with an inertial sensor and five optical markers (the right panel).

How NOKOV Contributes to the Research

The inertial sensor can measure the specific force, which is the vector difference between the actual body acceleration and the gravity vector and 3-D angular velocity data. The optical facility includes eight high-speed cameras, which can synchronously record the moving trajectory from their own view. When the object attached to the reflective markers moves within the view field of the cameras. The accuracy of the stereophotogrammetric system can be even higher than centimeters, up to the submillimeter, as described in \[49]. It should be noted that the layout of reflective balls is asymmetric, which ensures that the distance between any two balls is different. So, the optical camera system can still record the racket movement by capturing at least any two balls. The collection of a concreteobject movement is shown in Fig. 11. To keep time alignment, we uniformly adjust the sampling frequency of the optical and inertial sensors to 200 Hz. Therefore, the data collection of the two sensors can be synchronized.

Citation Wang Y, Zhao Y. Arbitrary spatial trajectory reconstruction based on a single inertial sensor[J]. IEEE Sensors Journal, 2023, 23(9): 10009-10022.

Link https://ieeexplore.ieee.org/document/10080916

Artificial Human Balance Control by Calf Muscle Activation Modelling

Keywords

Muscle stretch reflex, calf muscle activation, standing control, exoskeleton control

Abstract

The natural neuromuscular model has greatly inspired the development of control mechanisms in addressing the uncertainty challenges in robotic systems. Although the underpinning neural reaction of posture control remains unknown, recent studies suggest that muscle activation driven by the nervous system plays a key role in human postural responses to environmental disturbance. Given that the human calf is mainly formed by two muscles, this paper presents an integrated calf control model with the two comprising components representing the activations of the two calf muscles. The contributions of each component towards the artificial control of the calf are determined by their weights, which are carefully designed to simulate the natural biological calf. The proposed calf modelling has also been applied to robotic ankle exoskeleton control. The proposed work was validated and evaluated by both biological and engineering simulation approaches, and the experimental results revealed that the proposed model successfully performed over 92% of the muscle activation naturally made by human participants, and the actions led by the simulated ankle exoskeleton wearers were overall consistent with that by the natural biological response.

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How NOKOV Contributes to the Research

2) EXPERIMENTALPROTOCOL
A Nokov motion capture system (produced by Beijing Nokov Science & Technology Co., Ltd. China) with eight charge-coupled device cameras was employed for the vehicle kinematic data capturing. The camera system calibration and three-dimensional target reconstruction were performed by NK-cortex software (produced by Nokov, China). The vehicle kinematics were derived from 4 markers attached on the vehicle, and the participants kinematic were derived from 21 markers pasted on the joints of body-segments including head-arms-trunk, thigh, and shank-foot segments. The vehicle kinematic data were acquired at the frequency of 100Hz.

Citation Yin K, Chen J, Xiang K, et al. Artificial human balance control by calf muscle activation modelling[J]. IEEE Access, 2020, 8: 86732-86744.

Link https://ieeexplore.ieee.org/abstract/document/9086511

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Chained Spatial Beam Adomian Decomposition Model: A Novel Model of Flexible Slender Beams for Large Spatial Deflections

Keywords

explicit beam model, large spatial deflection, Adomian polynomials, quaternion, compliant mechanisms and robots, mechanisms and robots

Abstract

The main element of compliant mechanisms and continuum robots is flexible slender beams. However, the modeling of beams can be complicated due to the geometric nonlinearity becoming significant at large elastic deflections. This paper presents an explicit nonlinear model called the spatial beam Adomian decomposition model (SBADM) for intermediate spatial deflections of a slender beam with uniform, bisymmetric sections subjected to general end-loading. Specifically, the elongation, bending, torsion, and shear deformations of the beams are modeled based on Timoshenko's assumptions and Cosserat rod theory. Then, the quaternion transformation and Adomian decomposition are used to solve the nonlinear governing differential equations for the beam by truncating the higher-order terms, yielding an explicit expression for spatially deflected beams within intermediate deflection ranges. Simulations demonstrate the accuracy and time-wise efficiency of the SBADM, as well as its advantages over the state-of-the-art. In addition, this paper also introduces a discretization-based scheme called the chained SBADM (CSBADM) for large spatial deflections of flexible beams. Real-world experiments with two different configurations have also been performed to validate the effectiveness of the CSBADM. The results indicate that the CSBADM can accurately calculate the load–displacement relations for large deformed beams.

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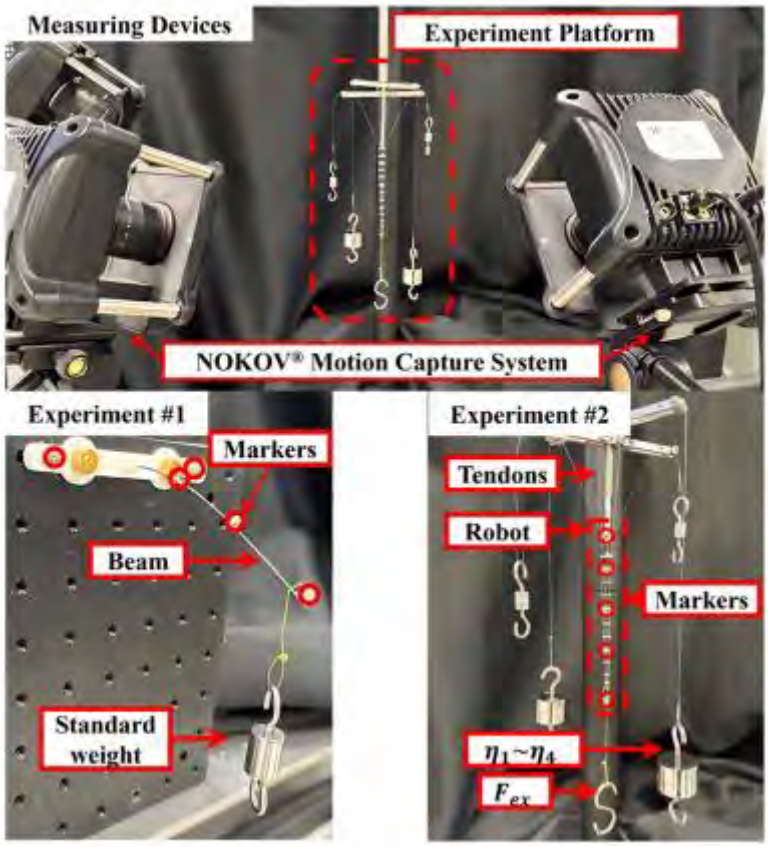

Fig. 9 Devices for experimental validation

How NOKOV Contributes to the Research

The validation system is shown in Fig.9. Some 3-mm-diameter markers reconstruct the profile of the beam. It's noticed that the offsets between each marker and its corresponding beam are measured before the experiment. The three-dimensional capture system consisting of five optical cameras (Mars 4H, NOKOV, China) with 180 Hz measures the robot deflections by capturing markers (only three cameras are shown in Fig.9). The 3D accuracy of the system is±0.40 mm.

Citation Chen Y, Chen G. Chained spatial beam adomian decomposition model: a novel model of flexible slender beams for large spatial deflections[J]. Journal of Mechanisms and Robotics, 2025, 17(5): 051010.

Link
https://asmedigitalcollection.asme.org/mechanismsrobotics/article/17/5/051010/1207812/Chained-Spatial-Beam-Adomian-Decomposition-Model-A?searchresult=1

Collective fission behavior in swarming systems with density-based interaction

Keywords

Swarming systems; Robotic swarm; Density field interaction; Collective fission behavior; Spontaneous split

Abstract

In this paper we revisit the self-organized collective behavior of swarms with density field interaction that is inspired from the model of smoothed particle hydrodynamics. For a homogeneous swarming system a novel collective fission behavior is seen to emerge where equal to or more than two sub-clusters spontaneously come from a single connected cluster. The focus of this study is on the analysis of collective fission behavior in trigger conditions, function manners and dynamic characteristics. For the first time, we are able to predict the stability of a single connected cluster, the trigger conditions of collective fission behavior, the number of sub-clusters and the group size of each sub-cluster. The analysis results also show that the collective fission behavior is irreversible by changing the control parameters and the group size. However, it is reversible when the sensing range is enlarged to encompass all sub-clusters. These characteristics are evaluated in simulations as well as on the real swarm robotic system. The study of collective fission behavior provides an elegant insight for how self-organized segregation emerges in biological swarms and artificial systems.

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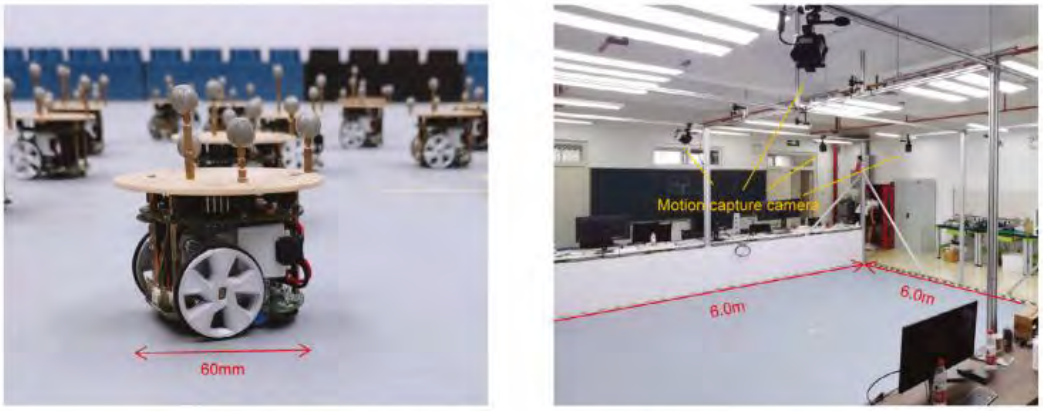

Fig. 8. SwarmBang robot and the overhead tracking system.

How NOKOV Contributes to the Research

Firstly, each robot needs to obtain the heading and position information of its local neighbors, which means the robot should have a localized sensing ability. To achieve this, we use the overhead tracking system, which can estimate the headings and positions of all robots in a global reference frame by employing a motion capture system manufactured by NOKOV. The information of headings and positions that contains all robots then is broadcasted to the working robots. For each working robot, it only decodes the information of positions and headings of its neighbors, such that the distributed computation is approximated.

Citation Zhang S, Lei X, Zheng Z, et al. Collective fission behavior in swarming systems with density-based interaction[J]. Physica A: Statistical Mechanics and its Applications, 2022, 603: 127723.

Link https://www.sciencedirect.com/science/article/abs/pii/S0378437122004794

Controlling Multi-Spacecraft Formations Under Eavesdropping Constraints: A ϵ-Nash Equilibrium Approach

Keywords

ϵ-Nash equilibrium, backstepping, eavesdropping, multi -spacecraft systems (MSS)

Abstract

This paper addresses the formation control problem for multi-spacecraft systems (MSS) in the presence of eavesdroppers. The spacecrafts in the system transmit information through a distributed communication topology, and the eavesdropping rate is modeled as distance-dependence. To mitigate the impact of eavesdropping, we design a control strategy based on ϵ-Nash equilibrium and the backstepping method, ensuring the spacecrafts achieve the desired formation while minimizing information leakage. Finally, we prove the stability of the proposed algorithm and the boundedness of ϵ. The effectiveness of the proposed approach is demonstrated through simulations with satellite clusters and experimental validation using wheeled robots.

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Fig. 6. Wheeled mobile robots physical verification platform.

How NOKOV Contributes to the Research

In this section, we demonstrate the effectiveness of the proposed method through two experiment sconducted on a physical platform. The experiment a platform for wheeled mobile robots features a Nokov Mars 2H optical 3D motion capture system, which includes 12 cameras with a resolution of 2.2 megapixels,a frame rate of 380 Hz, an image size of 2048 × 1088,and a latency of 2.4 ms. Additionally, the platform consists of a monitor computer (Lenovo Savior Blade7000) and four wheeled mobile robots (E-puck2). The configuration of the physical platform is illustrated in Fig.6.

Citation Zhong Y, Yuan Y, Yuan H. Controlling Multi-Spacecraft Formations Under Eavesdropping Constraints: A $\epsilon $-Nash Equilibrium Approach[J]. IEEE Transactions on Aerospace and Electronic Systems, 2025.

Link https://ieeexplore.ieee.org/abstract/document/10884777

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Cross-Domain Representation Learning for Clothes Unfolding in Robot-Assisted Dressing

Keywords

Clothes unfolding, Grasping point recognition, Robot-assisted dressing, Human-robot interactio

Abstract

Assistive robots can significantly reduce the burden of daily activities by providing services such as unfolding clothes and dressing assistance. For robotic clothes manipulation tasks, grasping point recognition is one of the core steps, which is usually achieved by supervised deep learning methods using large amount of labeled training data. Given that collecting real annotated data is extremely labor-intensive and time-consuming in this field, synthetic data generated by physics engines is typically adopted for data enrichment. However, there exists an inherent discrepancy between real and synthetic domains. Therefore, effectively leveraging synthetic data together with real data to jointly train models for grasping point recognition is desirable. In this paper, we propose a Cross-Domain Representation Learning (CDRL) framework that adaptively extracts domain-specific features from synthetic and real domains respectively, before further fusing these domain-specific features to produce more informative and robust cross-domain representations, thereby improving the prediction accuracy of grasping points. Experimental results show that our CDRL framework is capable of recognizing grasping points more precisely compared with five baseline methods. Based on our CDRL framework, we enable a Baxter humanoid robot to unfold a hanging white coat with a 92% success rate and assist 6 users to dress successfully.

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How NOKOV Contributes to the Research

We gather real depth images by constantly changing the hanging positions of the white coat with the help of the Kinect v2 camera. While taking depth images, the spatial Cartesian coordinates of the grasping points are recorded with a NOKOV Motion Capture System by placing markers at the collar areas. After repeating the above steps, we obtain a total of 5000 pieces of real labeled data, which takes approximately 50 hours. The non-clothing segments are filtered from the real images by thresholding the depth between 80 cm and 110 cm.

Citation Qie, J. et al. (2023). Cross-Domain Representation Learning for Clothes Unfolding in Robot-Assisted Dressing. In: Karlinsky, L., Michaeli, T., Nishino, K. (eds) Computer Vision – ECCV 2022 Workshops. ECCV 2022. Lecture Notes in Computer Science, vol 13

Link https://link.springer.com/chapter/10.1007/978-3-031-25075-0_44

CSI-Based Calibration Free Localization with Rotating Antenna for Coal Mine

Keywords

Indoor localization · Channel state information · Smartphone

Abstract

Accurate mine localization has always been an urgent demand. With the widespread emergence of cheap wireless devices in our life, channel state information (CSI) based indoor localization has attracted people's attention. In the existing CSI-based localization methods, fingerprint-based localization needs to build a huge database with poor robustness, and the methods based on angle of arrival (AOA) need specific antenna arrays and complex phase calibration. Because mobile devices such as smartphones only have one or two antennas, and the antennas inside the devices cannot form a receiving array, the conventional AOA estimation system cannot be deployed on such mobile devices. Therefore, we propose an AOA estimation method using rotating AP antennas. This method only needs one antenna at the receiving end to work and does not need to calibrate the phase. Firstly, the CSI phase of the rotating antenna is collected and the phase difference is calculated. Then, empirical mode decomposition (EMD) algorithm based on mutual information is used to remove the noise, and subcarrier selection is used to reduce the multipath effect in the data processing part. Finally, the AOA is estimated according to the relative position of the antenna. We conduct extensive experiments in mine and laboratory scenarios, and the median localization errors in mine and laboratory are 0.4 m and 0.6 m, the median angle errors are 4.2∘ and 5.2∘ respectively.

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(a) Laboratory (b) Mine

Fig. 7. Experimental scenarios

How NOKOV Contributes to the Research

4 Performance Evaluation
4.1 Experimental Scenarios
In the experiment, two TL-wdr 5610 are used as access points, and one nexus 6p with nexmon \[7] patch and bcm4358 wifi chip is used as receiver object. TL-wdr 5610 works in 2.4 GHz band, 20 MHz bandwidth, and has two omnidirectional antennas. Eight nokov optical 3D motion capture cameras were used to measure the ground truth. We choose the laboratory and mine for the experiment, and the experimental scene is shown in the Fig. 7.

Citation Zhang T, Zhang K, Liu D, et al. CSI-based calibration free localization with rotating antenna for coal mine[C]//International Conference on Wireless Algorithms, Systems, and Applications. Cham: Springer International Publishing, 2021: 263-274.

Link https://link.springer.com/chapter/10.1007/978-3-030-85928-2_21

CushionCatch: A Compliant Catching Mechanism for Mobile Manipulators via Combined Optimization and Learning

Abstract

Abstract—Catching flying objects with a cushioning process is a skill commonly performed by humans, yet it remains a significant challenge for robots. In this paper, we present a framework that combines optimization and learning to achieve compliant catching on mobile manipulators (CCMM). First, we propose a high-level capture planner for mobile manipulators (MM) that calculates the optimal capture point and joint configuration. Next, the pre-catching (PRC) planner ensures the robot reaches the target joint configuration as quickly as possible. To learn compliant catching strategies, we propose a network that leverages the strengths of LSTM for capturing temporal dependencies and positional encoding for spatial context (P-LSTM). This network is designed to effectively learn compliant strategies from human demonstrations. Following this, the post-catching (POC) planner tracks the compliant sequence output by the P-LSTM while avoiding potential collisions due to structural differences between humans and robots. We validate the CCMM framework through both simulated and real-world ball-catching scenarios, achieving a success rate of 98.70% in simulation, 92.59% in real-world tests, and a 28.7% reduction in impact torques. The open source code will be released for the reference of the community.

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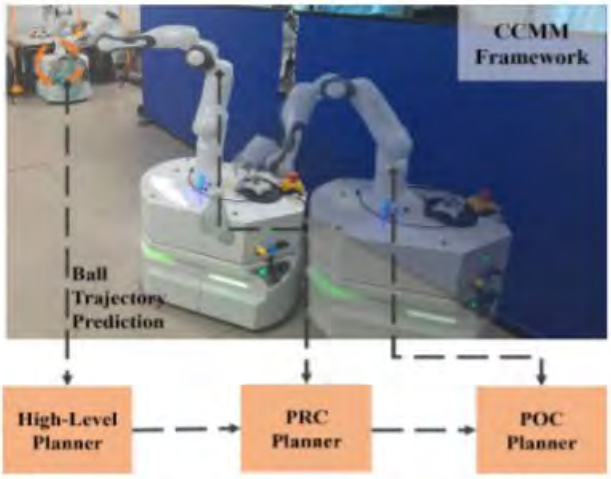

Fig. 1: The mobile manipulator's motions under CCMM framework for achieving compliant catching.

How NOKOV Contributes to the Research

We capture the velocity and position sequences of theball using a NOKOV motion-capture device during human-catching demonstrations as Fig. (5) shows. Reflective balls are placed on both the glove and the ball. We use the distancebetween them to determine when to start recording data. Intotal, 302 trajectories were collected. To distinguish betweeninputs and outputs of the data for the network, we identifiedthe point with the highest average velocity variation acrossall data points. This point is then used to split the sequenceinto input data and the corresponding output labels.

Citation B. Chen et al., "CushionCatch: A Compliant Catching Mechanism for Mobile Manipulators via Combined Optimization and Learning," 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hangzhou, China, 2025, pp. 105-112, doi: 10.110

Link https://ieeexplore.ieee.org/document/11246275

Design and Control of a Free-Floating Robot for Ground Microgravity Experiment

Keywords

Free-floating robot · Control · Trajectory planning · Ground microgravity experiment

Abstract

In this paper, a cube shaped free-floating robot that is composed of air-bearing, high-pressure gas tank, pressure reducing valve, solenoid valve, and nozzle is designed for ground microgravity experiment of on-orbit servicing missions. The attitude of the robot is controlled by a reaction wheel and the position of the robot is controlled by eight nozzles symmetrically distributed around itself. Their thrust is calibrated using the ballistic pendulum method and verified by a pressure sensor. To be able to control the robot accurately, the moment of inertia and the position of the mass center of the robot are obtained by experiments. To control the robot tracking an arbitrary trajectory, a trajectory planning method based on quintic polynomial curve interpolation and the hysteresis control law are applied in this paper. Simulation and experimental results show that the designed free-floating robot can achieve high precision using the presented trajectory planning method and control strategy.

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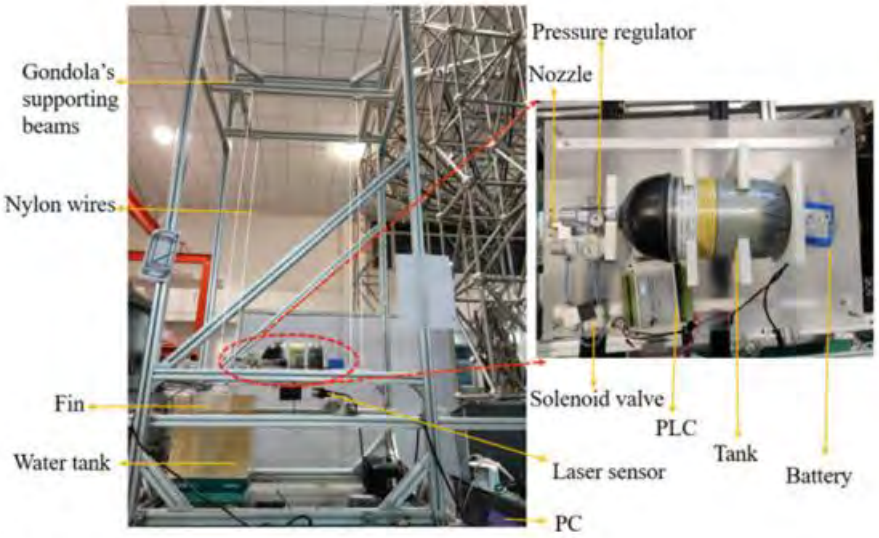

Fig. 5 The nozzle performance measurement system

How NOKOV Contributes to the Research

5 Experiment of Trajectory Tracking
5.l Experimental Platform
Due to low accuracy and inconvenience of measurement with small, portable displacement sensors available on the market, peripheral equipment is employed for the measurements in this study. Specifically, the NOKOV motion capture system developed by Beijing Nokov Science and Technology is used in experiment. This system uses infrared optical measurement methods, with several fuorescent balls arranged on the surface of the space air-floating robot as rigid bodies, continuously measuring their position to obtain the real-time position of the space air-floating robot. The measurement accuracy is in the sub-millimeter range, which satisfies the measurement requirements very well. The configuration of the position measurement system is shown in Fig. 16.

Citation Lin Y, Shan M. Design and Control of a Free-Floating Robot for Ground Microgravity Experiment[C]//International Conference on Mechanical System Dynamics. Singapore: Springer Nature Singapore, 2023: 3943-3962.

Link
https://ev.docapi.xyz/app/doc/?docid=cpx_M5c9f106219091b85c5fM67c310178165134&pageSize=25&index=1&searchId=4820f8f5cd414d7abf2b6107f1c02102&resultsCount=6&usageZone=resultslist&usageOrigin=searchresults&searchType=Quick

Design and functional validation of a needs-driven multifunctional integrated nursing wheelchair for elder individuals with disability

Keywords

ultifunctional care wheelchair, Omnidirectional mobility, Elderly care, Quality function deployment (QFD), Posture adjustment

Abstract

To address the complex care needs of elder individuals with disability, this study employs a Quality Function Deployment (QFD)-based approach to systematically prioritize functional requirements and guide the engineering design of a multifunctional intelligent wheelchair. The developed system integrates posture transition, omnidirectional mobility, toileting assistance, and bathing docking into a unified platform. Key innovations include a synchronized dual-actuator posture transition mechanism enabling progressive sit-to-stand support with phased center-of-gravity adjustment, a Mecanum wheel-based omnidirectional chassis for enhanced maneuverability in confined spaces, and a detachable waterproof backrest system facilitating transfer-free toileting and bathing operations. Prototype validation using CAD modeling and functional testing confirms that the integrated design significantly reduces the frequency of user transfers, minimizes secondary injury risks associated with positional changes, and improves overall caregiving efficiency and user comfort. Future work will focus on the development of multimodal interaction frameworks and adaptive decision-making systems to further enhance operational autonomy for users with communication impairments.

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Fig. 9 Experimental Evaluation of Posture Transition and Assisted Standing Functions

How NOKOV Contributes to the Research

Experimental results and discussion
No noticeable vibration or mechanical interference was observed during the experimental procedures, as assessed through direct visual inspection by the operator. To gain deeper insight into the wheelchair's posture transition capabilities, the NOKOV optical motion capture system was employed to synchronously record and analyze the joint angle parameters of both the wheelchair and the user throughout the transition process. As illustrated in Fig. 13, the changes in the user's knee joint angle (θ_k) and hip joint angle (Φ_h) exhibited a strong correlation with the corresponding variations in the wheelchair's knee joint angle (θ_w) and hip joint angle (Φ_w). Minor discrepancies between the two sets of measurements were attributed to the displacement of the knee joint's rotational center during flexion, which effectively altered the equivalent length of the lower leg. To compensate for this variation, an automatic footrest adjustment mechanism was introduced, enabling dynamic length correction of the user's lower leg and allowing full knee extension to 180°, thereby maintaining horizontal alignment with the wheelchair.

Citation Zhewen Z, Hongliu Y, Zhijie Z, et al. Design and functional validation of a needs-driven multifunctional integrated nursing wheelchair for elder individuals with disability[J]. Journal of NeuroEngineering and Rehabilitation, 2025, 22(1): 1-14.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001614801600002

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Distributed Maximum Correntropy Linear Filter Based on Rational Quadratic Kernel Against Non-Gaussian Noise

Keywords

distributed state estimation; rational quadratic kernel function; maximum correntropy criterion; non-Gaussian noise; consensus weight average

Abstract

This paper investigates the distributed state estimation problem for the linear system against non-Gaussian noise, where every sensor communicates information only within its adjacent sensors without the need for a fusion center. Correntropy is a similarity metric based on a kernel function that has symmetry. Symmetry means that for any two data points, the output value of the kernel function does not depend on the order of the data points. By adopting a correntropy cost function based on the rational quadratic kernel function approximation to restrain non-Gaussian heavy-tailed noise, a centralized maximum correntropy Kalman filter is first derived for the linear sensor network system. Then the corresponding centralized maximum correntropy information filter is attained by employing the information matrices, which is a foundation for further designing distributed information algorithms under multi-sensor networks. Thirdly, the distributed rational quadratic maximum correntropy information filter and distributed adaptive rational quadratic maximum correntropy information filter are designed by exploiting the weighted consensus average to solve the non-Gaussian heavy-tailed noise interference in sensor networks. Finally, the performance of the proposed algorithms is illustrated through numerical simulations on the sensor network system.

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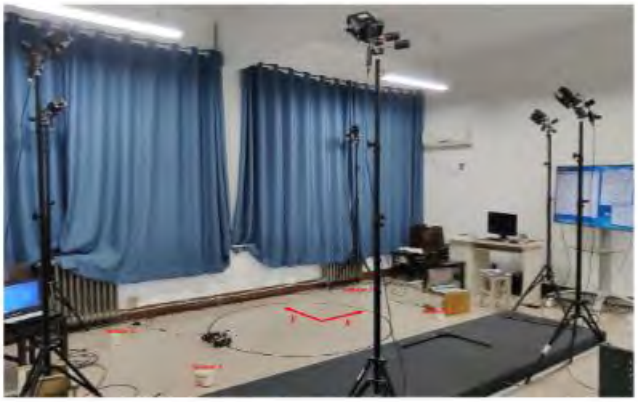

Figure 10. Target tracking experimental testbed.

How NOKOV Contributes to the Research

5.Experimental Setup for Multi-Sensor Target Tracking
5.1. Experimental Setup and Parameter SettingsTo assess the practical performance of the proposed estimator, a multi-sensor experi.mental platform was constructed for the task of dynamic target tracking, as illustrated in Figure 10. The platform consists of a test vehicle equipped with an electromagnetic drive.a Nokov motion capture system with six Mars 2 cameras, 24 GHz millimeter-wave radarsensors, and multiple PCs for data acquisition and processing, and so on. The motion capture system provides sub-millimeter accuracy and serves as the ground-truth reference for the target's position.

Citation Zhao X, Mu D, Yang J. Distributed Maximum Correntropy Linear Filter Based on Rational Quadratic Kernel Against Non-Gaussian Noise[J]. Symmetry, 2025, 17(6): 955.

Link https://www.mdpi.com/2073-8994/17/6/955

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Dynamic Formation Planning and Control for Robot Soccer Game with Multi-Agent Reinforcement Learning and Behavioral Model

Keywords

Legged locomotion, Games, Reinforcement learning, Planning, Teamwork, Synchronization, Robots, Sports, Convergence, Multi-agent systems

Abstract

The robot soccer game has been considered as an illustrative scenario to test the performance of research outcomes on multi-agent systems (MAS). While various algorithm has been developed for a robot soccer game and implemented in the RoboCup competition, relatively little collaboration can be found in existing results, e.g., the formation for passing and dribbling during the offense or the collaborative obstruction during defense, which are very common in the teamwork of human soccer game. This paper focuses on the collaboration problem in robot soccer games and proposes a dynamic formation planning and control strategy. Specifically, the offensive team maintains a desired formation and transits among the tasks of catching, passing, dribbling, and kicking based on a behavioral model. The defensive team is regulated by a reinforcement-learning-based policy network and dynamically forms a barrier to obstruct the offender. The strategies of both teams will swap according to the evolving situation of the match. Both simulation studies and real-world experiments are carried out to illustrate the performance of the proposed method, and the convergence to the desired formation is also rigorously proved.

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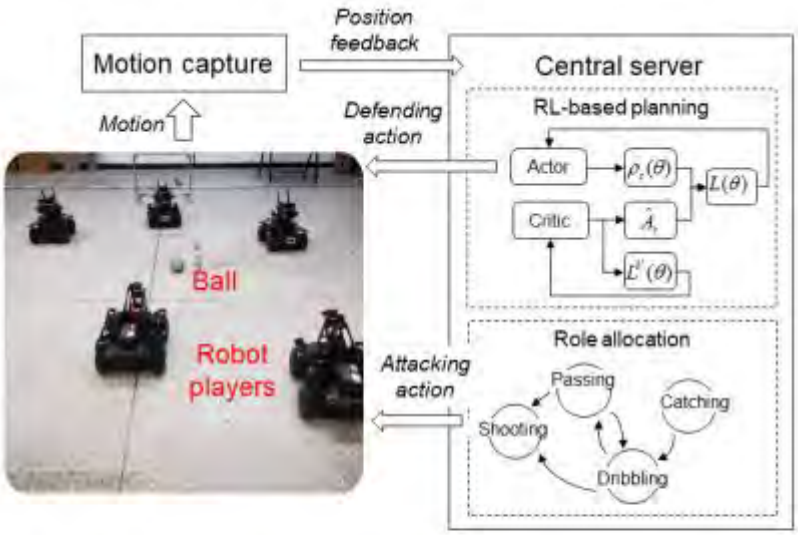

Fig. 2. The motion of all the robots and the ball is tracked by the motion capture and then sent to the central server. Two types of planning and control algorithms are realized in the server: On the offensive side, a behavioral model is constructed to drive multiple robots to catch, pass, dribble, and shoot the ball; On the defensive side, a reinforcement learning method is designed to allow robots to form barriers to obstruct them.

How NOKOV Contributes to the Research

Optical motion capture (OMC): The Nokov motioncapture system is comprised of 12 cameras. On everycamera mounts an Infra-Red (IR) LED around the lens,along with IR pass filters placed over the camera lens.By using motion capture, the real-time position of eachmoving reflective marker in the playing area can beachieved in 2.4ms with a positional error of less than0.2mm.

Citation Zhu H, Zhong H, Yan B, et al. Dynamic Formation Planning and Control for Robot Soccer Game with Multi-Agent Reinforcement Learning and Behavioral Model[C]//2024 International Conference on Advanced Robotics and Mechatronics (ICARM). IEEE, 2024: 837-842.

Link https://ieeexplore.ieee.org/document/10715990

Efficient modal parameter identification using DMD-DBSCAN and rank stabilization diagrams

Keywords

Dynamic mode decomposition， Data-driven， Density-based spatial clustering of applications with noise， modal parameter identification， stabilization diagram

Abstract

Modal parameter identification of aerospace structures, particularly improving the efficient using time-domain vibration responses, is currently a topic of great interest in structural dynamics. Data-driven Dynamic Mode Decomposition (DMD) technique in fluid dynamics has shown good potential for identifying the flow mode. In this respect, there have been a few studies on the application of DMD technique in structural dynamics. This paper proposes an efficient structural modal parameter identification method that combines the DMD technique and Density-based Spatial Clustering of Applications with Noise (DBSCAN) algorithm, called the DMD-DBSCAN method. Combined with the proposed rank stabilization diagram, the spurious modes produced by the DMD technique can be effectively cleaned by using DBSCAN algorithm to obtain the physical modal parameter. A numerical case of a composite wing model is presented to validate the proposed method, particularly when identifying the closely spaced modes. It has been shown that the rank stabilization diagram is more appropriate for DMD technique when compared with the solely existing sampling frequency stabilization diagram. An experiment on an aircraft model with response from three-dimensional optical technique is used to demonstrate the method's ability to deal with real complex structures. Compared with traditional methods, results show that the proposed DMD-DBSCAN method can accurately identify modal parameters of complex structures and has excellent operational efficiency because it is free from high order Hankel matrix construction. The proposed datadriven modal parameter identification method is efficient and promising for analysis of complex structures with large datasets.

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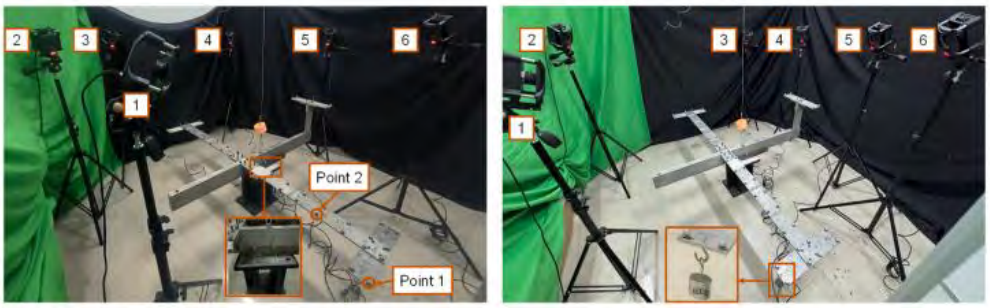

a b

Fig. 12. The static displacement measurements under two camera configurations. (a) configuration 1, (b) configuration 2.

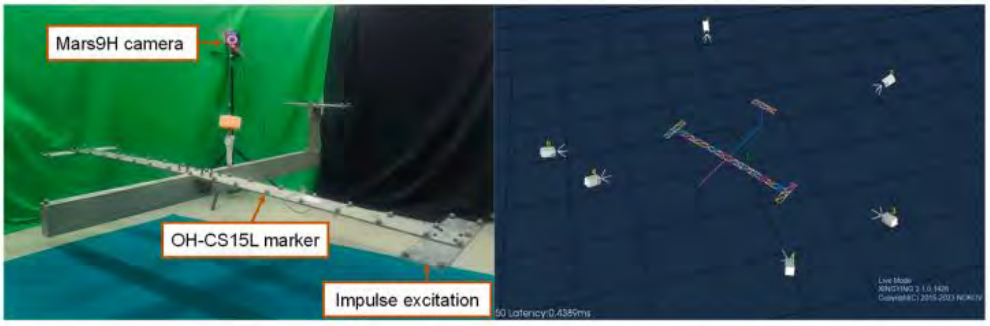

Fig. 13. The dynamic response test setup, geometric model and camera position in NOKOV motion capture system.

How NOKOV Contributes to the Research

Then, the proposed DMD-DBSCAN method is implemented on the response of displacement, measured by the NOKOV motion capture system with a three-dimensional optical technique.
The NOKOV motion capture system , which is based on the three-dimensional optical technique of sub-millimeter accuracy, was sed to measure displacement at multiple locations throughout the aircraft model.

Citation Wu C, Yang Z, He S. Efficient modal parameter identification using DMD-DBSCAN and rank stabilization diagrams[J]. Aerospace Science and Technology, 2025, 161: 110112.

Link
https://www.sciencedirect.com/science/article/abs/pii/S127096382500183X#:~:text=Efficient%20DMD-DBSCAN%20method%20for%20identifying%20modal%20parameters.%20A,closely%20spaced%20modes%20using%20a%20composite%20wing%20model.

Enhancing Generalizable 6D Pose Tracking of an In-Hand Object With Tactile Sensing

Keywords

Force and tactile sensing, sensor fusion, visual tracking

Abstract

When manipulating an object to accomplish complex tasks, humans rely on both vision and touch to keep track of the object's 6D pose. However, most existing object pose tracking systems in robotics rely exclusively on visual signals, which hinder a robot's ability to manipulate objects effectively. To address this limitation, we introduce TEG-Track, a tactile-enhanced 6D pose tracking system that can track previously unseen objects held in hand. From consecutive tactile signals, TEG-Track optimizes object velocities from marker flows when slippage does not occur, or regresses velocities using a slippage estimation network when slippage is detected. The estimated object velocities are integrated into a geometric-kinematic optimization scheme to enhance existing visual pose trackers. To evaluate our method and to facilitate future research, we construct a real-world dataset for visual-tactile in-hand object pose tracking. Experimental results demonstrate that TEG-Track consistently enhances state-of-the-art generalizable 6D pose trackers in synthetic and real-world scenarios.

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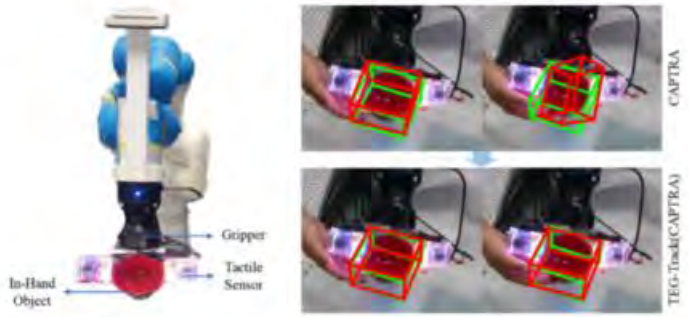

Fig. 1. We propose a general in-hand object pose tracking framework TEG-Track, and evaluate it on our synthetic and real datasets. Our approach enhances generalizable visual trackers such as BundleTrack [7] with tactile sensing. Here we visualize the tracking task as tracking the object's 3D bounding box: green boxes denote ground truth poses whereas red boxes denote estimated poses.

Fig. 5. (a) Data capturing system. Red, green, blue and yellow boxes indicate the Xarm robot arm with Geisight tactile sensors, the Realsense D415 RGB-D sensor, the NOKOV motion capture suite and the in-hand tracked object, respectively. (b) Object categories and instances.

How NOKOV Contributes to the Research

As illustrated in Fig. 5, in our real-world scenario, we additionally set up a NOKOV motion capture system to obtain the ground-truth object poses.

Citation Y. Liu et al., "Enhancing Generalizable 6D Pose Tracking of an In-Hand Object With Tactile Sensing," in IEEE Robotics and Automation Letters, vol. 9, no. 2, pp. 1106-1113, Feb. 2024, doi: 10.1109/LRA.2023.3337690.

Link https://ieeexplore.ieee.org/document/10333330

Enhancing robotic skill acquisition with multimodal sensory data: A novel dataset for kitchen tasks

Abstract

The advent of large language models has transformed human-robot interaction by enabling robots to execute tasks via natural language commands. However, these models primarily depend on unimodal data, which limits their ability to integrate diverse and essential environmental, physiological, and physical data. To address the limitations of current unimodal dataset problems, this paper investigates the novel and comprehensive multimodal data collection methodologies which can fully capture the complexity of human interaction in the complex real-world kitchen environments. Data related to the use of 17 different kitchen tools by 20 adults in dynamic scenarios were collected, including human tactile information, EMG signals, audio data, whole-body movement, and eye-tracking data. The dataset is comprised of 680 segments (~11 hours) with data across seven modalities and includes 56,000 detailed annotations. This paper bridges the gap between real-world multimodal data and embodied AI, paving the way for a new benchmark in utility and repeatability for skill learning in robotics areas.

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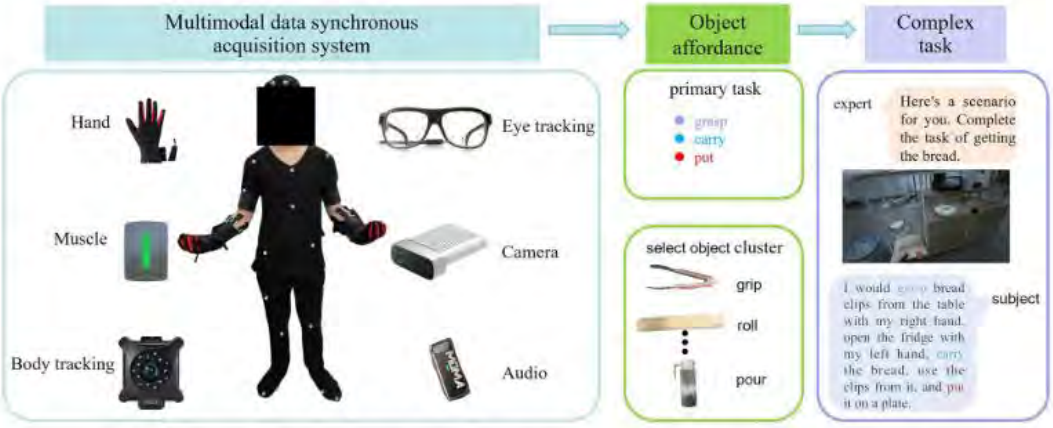

Fig. 1 Data capture system. The project focuses on a human-centered perspective, capturing multimodal information from wearable and external devices in a kitchen scenario.

How NOKOV Contributes to the Research

Nokov contains TRB and CAP files, which can be opened with the official software, as well as exported common 3D files. The data includes mechanical sensors, pre-processed exported hand model video, and various files. Official software can open TRB and CAP files for Nokov and export them as TRC files. The TRC file can be opened with software like Microsoft Excel and contains the following attributes: The data format frame, time, timestamp, XYZ coordinates.

Citation Ren, R., Wang, Z., Yang, C., Liu, J., Jiang, R., Zhou, Y., ... & He, B. (2025). Enhancing robotic skill acquisition with multimodal sensory data: A novel dataset for kitchen tasks. Scientific Data, 12(1), 476.

Link https://www.nature.com/articles/s41597-025-04798-z

Fast Fiber Shape Sensing with High Accuracy by a two-layer LSTM Network

Abstract

The visualization and navigation of minimally invasive instruments within confined internal spaces are critical to the success of the surgery, but traditional navigation methods face challenges from electromagnetic interference and ionizing radiation. To address these limitations, we propose a fast fiber shape sensing approach with high accuracy based on a two-layer long short-term memory (LSTM) network. The model directly regresses the 3D coordinates along the fiber sensor from the Bragg wavelength shifts of fiber Bragg gratings (FBGs), bypassing explicit curvature estimation and numerical integration. In dynamic experiments, the method achieves real-time inference at 32 fps with an end-to-end latency of approximately 7.3 ms. The mean tip error is around 2.9 mm, accounting for 0.72% of the 400 mm sensing length. The results indicate that the proposed two-layer LSTM-based method enables high-speed, high-accuracy fiber shape reconstruction, offering potential for real-time fiber navigation applications.

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How NOKOV Contributes to the Research

Figure 1 shows the principle of fiber shape sensing based on the LSTM method. As shown in Fig. 1(a), the shape sensor consists of three single-mode fibers (SMFs) with UV-inscribed FBGs, bonded to a NiTi alloy wire using 353ND optical glue. Each bare fiber has a diameter of 200 μm and carries 10 uniformly spaced FBGs along the sensing region. Each grating has a length of 5 mm, with a spacing of 40 mm between adjacent gratings, resulting in a total sensing length of 400 mm. The FBGs are spectrally multiplexed with staggered central wavelengths ranging from 1528.0 nm to 1559.5 nm to avoid spectral overlap and ensure channel separation. Then, a commercial high-speed FBG interrogator with 1-dBm optical power demodulates the Bragg wavelengths from all sensing points, while the 3D positions of passive markers on the sensor surface are simultaneously captured by a motion-capture system (Nokov, China), as illustrated in Figs. 1(b) and 1(c). The motion-capture system records coordinates data of markers in real time at 180 fps with a spatial accuracy of 0.1 mm, and the FBG interrogator streams the Bragg wavelengths at 2 kHz. A global timestamp synchronizes the two data streams from motion-capture system and interrogator with millisecond-level misalignment, and motion-capture frames with occlusion-flagged invalid markers were discarded. These synchronized wavelength and coordinate measurements without an additional temporal filter are subsequently used to train the network and to predict the 3D coordinates along the sensing fiber, as depicted in Fig. 1(d).

Citation Zheng X, Zhou T, Fan Y, et al. Reconstruction accuracy enhancement of fiber shape sensing by Kabsch-algorithm-based pose correction[J]. Optics Express, 2026, 34(4): 7208-7219.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001682097900001

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Forward Kinematics of Object Transporting by a Multi-Robot System With a Deformable Sheet

Keywords

Object handling and transporting, multi-robot system, forward kinematics, deformable sheet

Abstract

We present a forward kinematics method for object handling and transporting by a multi-robot team with a deformable sheet as a carrier. Due to the deformability of the sheet and the high dimension of the whole system, it is challenging to clearly describe all the possible positions of the object on the sheet for a given formation of the multi-robot system. A complete forward kinematics (FK) method is proposed for object handling by an N-mobile robot team with a deformable sheet. Based on the virtual variable cables model, a constrained quadratic problem (CQP) is formulated by combining the geometric constraints and minimum potential energy conditions of the system. Analytical solutions to the CQP are presented and then further verified with the force closure condition. We present a computational algorithm based on the FK method to obtain all possible solutions with the given initial sheet shape and the robot team formation. We demonstrate the effectiveness, completeness, and efficiency of the FK algorithm with experimental results and case study examples.

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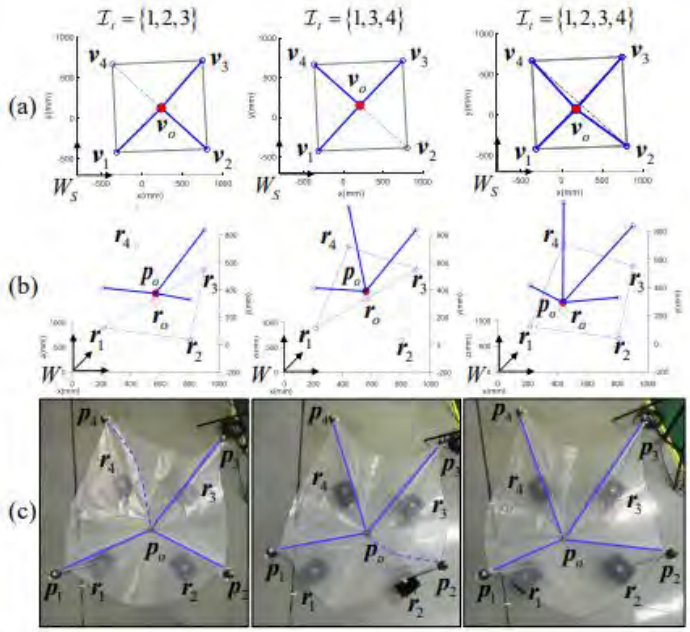

Fig. 4. Example 1: Experimental and computational results for three FK solutions of the four-robot formation to handle an object with a deformable sheet. $\mathcal{V}_N^0 = [-0.32\ -0.42;\ 0.80\ -0.38;\ 0.75\ 0.71;\ -0.37\ 0.66]^T$ m, and $\mathcal{R}_N = [0.21\ 0.12;\ 0.80\ 0.04;\ 0.90\ 0.55;\ 0.44\ 0.72]^T$ m. A straight line segment (taut cable) is formed when the plastic sheet is subject to tension and marked by a blue solid line. (a) The contact point $\boldsymbol{v}_o$ between the object and the sheet in $\mathcal{W}_S$. (b) The object position $\boldsymbol{p}_o$ and robot configuration $\mathcal{R}_N$ in $\mathcal{W}$. (c) The snapshots of experimental system configuration.

How NOKOV Contributes to the Research

The elastic deformation of the sheet during the experiment can be ignored. The position of the holding points and the object were measured by the motion capture system(6 cameras from NOKOV)at a rate of 60 Hz. The robot had a differential wheel structure driven by two stepper motors with an embedded system (Arduino UNO R3). The communication among robots was implemented by the ZigBee wireless network protocol for low-speed and short-distance transmission.

Citation Hu J, Liu W, Yi J, et al. Forward kinematics of object transporting by a multi-robot system with a deformable sheet[J]. IEEE Robotics and Automation Letters, 2024, 9(4): 3459-3466.

Link https://ieeexplore.ieee.org/abstract/document/10443023

Hierarchical Consensus-Based Multi-Agent Reinforcement Learning for Multi-Robot Cooperation Tasks

Abstract

In multi-agent reinforcement learning (MARL), the Centralized Training with Decentralized Execution (CTDE) framework is pivotal but struggles due to a gap: global state guidance in training versus reliance on local observations in execution, lacking global signals. Inspired by human societal consensus mechanisms, we introduce the Hierarchical Consensus-based Multi-Agent Reinforcement Learning (HC-MARL) framework to address this limitation. HC-MARL employs contrastive learning to foster a global consensus among agents, enabling cooperative behavior without direct communication. This approach enables agents to form a global consensus from local observations, using it as an additional piece of information to guide collaborative actions during execution. To cater to the dynamic requirements of various tasks, consensus is divided into multiple layers, encompassing both short-term and long-term considerations. Short-term observations prompt the creation of an immediate, low-layer consensus, while long-term observations contribute to the formation of a strategic, high-layer consensus. This process is further refined through an adaptive attention mechanism that dynamically adjusts the influence of each consensus layer. This mechanism optimizes the balance between immediate reactions and strategic planning, tailoring it to the specific demands of the task at hand. Extensive experiments and real-world applications in multi-robot systems showcase our framework ' s superior performance, marking significant advancements over baselines.

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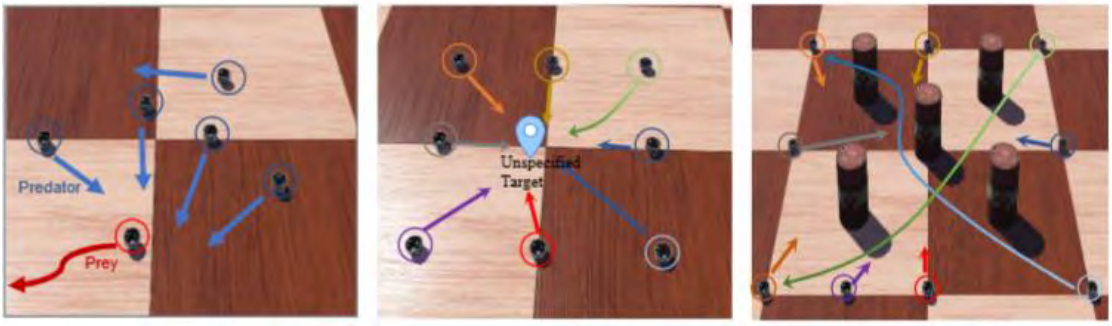

How NOKOV Contributes to the Research

We validated the real-world applicability of HC-MARL by conducting experiments on E-puck swarm. We utilized the NOKOV motion capture system for indoor positioning.

Citation Feng P, Liang J, Wang S, et al. Hierarchical consensus-based multi-agent reinforcement learning for multi-robot cooperation tasks[C]//2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2024: 642-649.

Link https://ieeexplore.ieee.org/abstract/document/10802212

HMC-SLAM: A Robust VSLAM Based on RGB-D Camera in Dynamic Environment Combined Hierarchical Multidimensional Clustering Algorithm

Keywords

Depth information, dynamic environment, hierarchical clustering, simultaneous localization and mapping (SLAM)

Abstract

Most of the current visual simultaneous localization and mapping (SLAM) systems assume that the working environment is static, but dynamic targets in the actual working environment will reduce the position estimation accuracy. Aiming at the problem that visual SLAM cannot filter dynamic targets in a dynamic environment, this article proposes a visual SLAM (VSLAM) system for a dynamic environment based on hierarchical multidimensional clustering (HMC) of feature points, called HMC-SLAM, which can effectively reduce the localization error in dynamic environments. The system identifies a dynamic detection box by combining semantic information and polar geometric constraints. In the dynamic detection box, feature point clusters are divided by fusing the polar distance and depth information of feature points. During the process of dynamic feature point cluster removal, the strongest dynamic point cluster is first identified, and then the adjacent point clusters in its depth range are removed together. To further refine the rejection, we define optimized weights for the feature points in the detection box to avoid the influence of potential dynamic points. In the experiments, we evaluate the performance of the proposed HMC-SLAM in the TUM and BONN datasets and real scenarios. In the TUM and BONN datasets, the algorithmic accuracy and stability of HMC-SLAM are improved by 80.37% and 87.48% relative to ORBSLAM3, respectively. The real scenario results show that HMC-SLAM maintains good localization accuracy, effectively rejects dynamic targets, and is more robust than the current state-of-the-art dynamic SLAM methods.

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(a) (b) (c)

Fig. 7. (a) Intel Realsense D455 camera. We built an experimental scene as shown in (b) using a broom, a cardboard box, and a chair. (c) NOKOV metric optical 3-D motion capture device.

How NOKOV Contributes to the Research

To further evaluate the performance of HMC-SLAM, we designed a real-world environment to assess the algorithm's trajectory and reconstruction accuracy. We conducted the experiments by constructing a real scene in a motion capture lab, which is approximately 6×6 m in size. We captured RGB-D information using an Intel Realsense D455 handheld camera with motion capture flags at a resolution of 640×480 and a frame rate of 30 fps. The trajectory of the camera operation was also captured using a NOKOV metric optical 3-D motion capture system. The experimental environment and equipment are shown in Fig. 7.

Citation Xu B, Zheng Z, Pan Z, et al. HMC-SLAM: A Robust VSLAM Based on RGB-D Camera in Dynamic Environment Combined Hierarchical Multidimensional Clustering Algorithm[J]. IEEE Transactions on Instrumentation and Measurement, 2025.

Link https://ieeexplore.ieee.org/document/10926921

Humanoid Grasping with Multi-Finger Dexterous Hands Based on DM-KMP

Keywords

Service robots, Shape, Humanoid robots, Grasping, Robot sensing systems, Robustness, Trajectory

Abstract

Humanoid grasping plays a crucial role in robotic manipulation. Currently, most humanoid grasping methods exhibit limitations in control and generalization when handling complex and diverse grasping tasks. In this study, we proposed a novel humanoid grasping control method based on dynamic movement primitives (DMP) and kernelized movement primitives (KMP), namely DM-KMP. We conducted an experiment involving the grasping of 12 different objects using a multi-finger dexterous hand. The results showed that the DM-KMP method achieved a success rate of 90.8%, significantly higher than the 77.5% success rate of the traditional KMP method and the 81.7% success rate of the DMP method. These findings indicated that the proposed DM-KMP method could not only improve the grasping performance for multi-finger robotic hands but also show flexibility of modulating the reference trajectories, making it more suitable for complex and varied grasping tasks. This novel method may improve the performance of grasping with multi-finger dexterous hand and can be widely applied in a variety of application such as industrial or in-house manipulative tasks.

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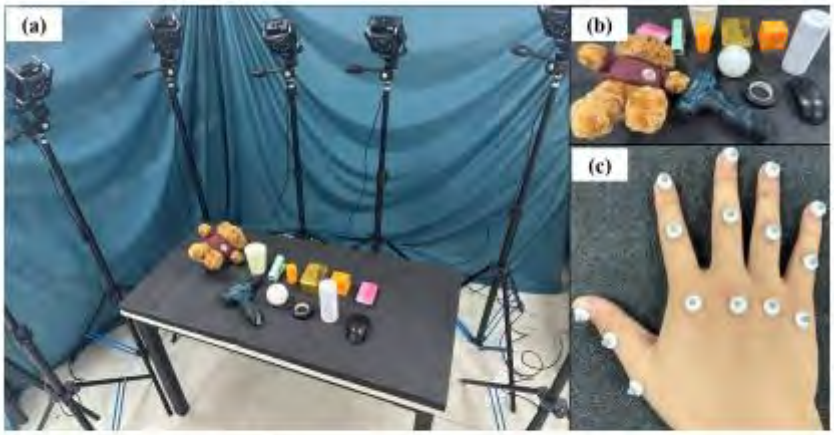

Fig. 2: Experimental scene. (a) Experimental equipment. (b) Objects. (c) Reflective marker points.

How NOKOV Contributes to the Research

The expert demonstrators in this study had extensive experience in grasping, were familiar with the use of the equipment, and were able to ensure that their hand motion trajectories were fully captured, thereby ensuring data accuracy. The experiments employed the NOKOV Motion Capture System, a high-precision motion capture system comprising multiple high-frame-rate cameras and motion capture sensors. These devices were capable of recording the demonstrators' hand motion trajectories and joint angles in real-time while grasping objects, thereby ensuring the precision and completeness of the data.

Citation Wang J, Li K. Humanoid Grasping with Multi-Finger Dexterous Hands Based on DM-KMP[C]//2024 WRC Symposium on Advanced Robotics and Automation (WRC SARA). IEEE, 2024: 34-39.

Link https://ieeexplore.ieee.org/abstract/document/10685732

I-KAN: Reconstructing Over-Range Inertial Signals

Keywords

Inertial sensor, Over-range, Signal reconstruction, KAN, Generation hallucination

Abstract

Inertial sensors are widely used in modern society, covering automotive, aerospace, robotics, and consumer electronics. However, these widely used sensors suffer from range limitations, causing signal saturation and information loss under high-dynamic motion conditions. To address this problem, we introduce the Kolmogorov-Arnold Networks (KAN) into inertial sensor signal processing for the first time and propose the I-KAN model. Unlike traditional deep learning models that treat signals as discrete point sequences, KAN treats the signal as a continuous curve through embedded spline functions, which allows it to infer the lost signal segments by exploring the continuity and fluctuation patterns of signal curves. Moreover, considering deep learning models suffer from the hallucination problem that generates chaotic and spurious outputs, we propose the Generation Hallucination Entropy (GHE), which quantifies and reduces hallucinations by enhancing the consistency of outputs for similar inputs, thus improving the stability and reliability of the model. Given the absence of research and dataset for reconstructing inertial over-range signals, we release the first inertial over-range signal recovery dataset (IOSRD) in Github, which consists of inertial sensor data from 10 smartphones. The results demonstrate that I-KAN effectively handles varying degrees of signal saturation and sets a benchmark in inertial over-range signal reconstruction.

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How NOKOV Contributes to the Research

During the data collection process, each smartphone was subjected to vigorous shaking in multiple directions, as illustrated in Fig. 3. Moreover, an eight-camera optical equipment (Nokov Mars2H) is employed to assist in motion capture. All experiments are implemented by Pytorch with NVIDIA RTX 4090 GPU.

Citation Wang Y, Zhang S, Zhao Y. I-kan: Reconstructing over-range inertial signals[C]//ICASSP 2025-2025 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP). IEEE, 2025: 1-5.

Link https://ieeexplore.ieee.org/document/10887612

Joint torque estimation for the human arm from sEMG using back propagation neural networks and auto encoders

Keywords

Joint torque estimation; Surface electromyography; Backpropagation neural networks; Autoencoder

Abstract

Estimation of joint torque for human arm is important to help a robot adapt to a human partner in human-robot collaboration. In this study, we proposed an estimating model combined the back propagation neural networks (BPNN) and autoencoders to estimate the joint torque of human arm from surface electromyography (sEMG). Autoencoders were used to select the appropriate features of sEMG signals. The joint angles obtained from a vision-system were combined with the sEMG features, which were set as the input data for the estimating model. A 4-layer BPNN was used to map the sEMG features to the joint torque. The proposed estimating model was compared to other five models through experiments by estimating shoulder joint torque and elbow joint torque. The root mean square error and correlation coefficient between the estimated joint torque value and a theoretic value calculated by inverse dynamics were used to evaluate the proposed model. The root mean square error and correlation coefficient for the proposed model is 1.3842 and 0.9439, respectively. Experimental results showed that the proposed model can derive lower root mean square error and higher correlation coefficient by comparing to other models, which indicates the proposed model can estimate more accurate joint torque from sEMG than other models.

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Fig. 1. Camera arrangement of the vision system.

How NOKOV Contributes to the Research

In this paper, we collected the information from the sEMG and vision system to build a model that can estimate the joint torque of the human arm. A vision system (Nokov Mars 1.3H) was used to capture the motion of the human arm. Angles of the shoulder joint and elbow joint were calculated based on the visual information. The vision system, which consisted of eight high-speed infrared cameras, recorded the 3-D position of the markers in the world coordinate frame at a frequency of 100 Hz (Fig. 1). To obtain enough information, we regarded the upper arm as link L1 and combined the forearm and hand as link L2. Then,the whole arm was simplified as a two-link structure. Five markers, A, B, C, D, and E, were attached to the human arm. Marker A was on the shoulder. Marker B was on the center of mass of link L1. Marker C was on the elbow. Marker D was on the center of mass of link L2, and marker E was on the end of the hand (Fig. 2). Additionally, an L-shaped rod with four markers was placed on the ground as the reference coordinate frame for motion analysis.

Citation Huang Y, Chen K, Zhang X, et al. Joint torque estimation for the human arm from sEMG using backpropagation neural networks and autoencoders[J]. Biomedical Signal Processing and Control, 2020, 62: 102051.

Link https://www.sciencedirect.com/science/article/pii/S174680942030207X

Mean-Shift Shape Formation of Multi-Robot Systems Without Target Assignment

Abstract

The methods of shape formation in robot swarms are usually classified into two categories by whether assignment is used or not. The first is to use target assignment to assemble precise formation. However, the additional algorithm for re-assignment is required to handle unreasonable situations, which results in lower efficiency. The second, also called assignment-free method, is to use local behaviors to assemble formation, however, existing methods can rarely achieve the precise formation. In this letter, we present a distributed assignment-free algorithm to achieve the precise shape formation based on the mean-shift algorithm. Specifically, each target location in robot's perception range is equally regarded as a point of the mean-shift vector. Then, the weight value of each point is computed according to the density of the target location. Here, each robot obtains the density of the target location according to the distribution of its neighbors. Moreover, this density calculation also considers the states of non-neighboring robots via the hop-count algorithm, thus avoiding conflicts among robots. Subsequently, each robot can regard the calculated mean-shift vector as its control command. Finally, simulation results show that our algorithm can form precise shapes at least 8 times more efficient than the assignment-based approach and physical experiment results confirm that the proposed algorithm exhibits promising potential for practical applications.

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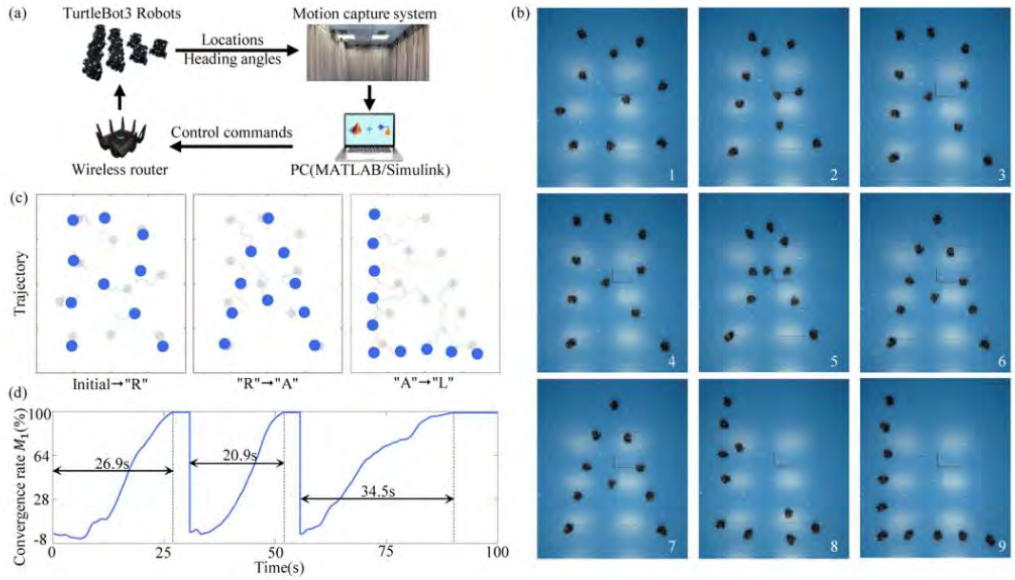

Fig. 7. System configuration and experiment results. (a) Experiment system configuration. (b) Snapshots of the experiment in forming "R," "A," and "L." The snapshots 1–3, 4–6, and 7–9 show the robots from initial state to the letter "R," the letter "R" to "A," and the letter "A" to "L," respectively. (c) Trajectories of the experiment process. (d) The convergence rate of the experiment over time.

How NOKOV Contributes to the Research

The Nokov Mocap system is used to obtain real-time positions of robots.

Citation Y. Zhang, R. Zhou, X. Li and G. Sun, "Mean-Shift Shape Formation of Multi-Robot Systems Without Target Assignment," in IEEE Robotics and Automation Letters, vol. 9, no. 2, pp. 1772-1779, Feb. 2024, doi: 10.1109/LRA.2024.3349926.

Link https://ieeexplore.ieee.org/document/10380669

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Mechanical Metamaterials with Discontinuous and Tension/Compression-Dependent Positive/Negative Poisson's Ratio

Keywords

Additive manufacturing, auxetic materials, deformations, discontinuous Poisson's ratios, mechanical metamaterials

Abstract

Ordinary materials have positive Poisson's ratios (PRs), and the currently known mechanical metamaterials possess negative PRs both under tension and compression. Herein, two types of novel cellular structure units with tension/compression-dependent positive/negative PRs are demonstrated. For type I structure, the unit exhibits a positive PR during tension and a negative PR during compression, while for type II structure, the unit shows a negative PR during tension and a positive PR during compression. The deformation behaviors of the new metamaterials are first predicted by a simple analytical model and finite-element method calculations, and the predicted results are then confirmed experimentally. Numerical and experimental studies show that for the plane angle $\alpha < 90°$, the unit of the new metamaterial switches its PR under compression and exhibits a discontinuous change in the PR. The deformation law does not depend on either the Young's modulus or the hardness of the material. The geometrically determined deformation behaviors of the proposed metamaterials are observed in 2D and 3D cellular structures and are proven to be robust through numerical and experimental studies. The proposed mechanical metamaterials can be applied as new deformation-protected materials in energy-absorbing devices, soft robotics, and tissue engineering scaffolds and as thermal deformation materials.

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How NOKOV Contributes to the Research

Many half spheres used as tracing points were glued onto a sam-ple to measure its deformation. Then, six cameras of the motion capture system emitted infrared radiation that was reflected by the half spheres and received by the cameras. Then, the positions of the sphere centers were calculated by the system. The radius of the half spheres was 2.5 mm. The centers of the half spheres were aligned with that of the connecting disks (defined in Figure 3a). A photograph of the experimental setup is shown in Supporting Information.

Citation Yang N, Deng Y, Zhao S, et al. Mechanical metamaterials with discontinuous and tension/compression-dependent positive/negative Poisson's ratio[J]. Advanced Engineering Materials, 2022, 24(3): 2100787.

Link https://onlinelibrary.wiley.com/doi/abs/10.1002/adem.202100787

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MHTrack: mmWave-based Mobile Hand Tracking

Keywords

mmWave radar, hand tracking, gesture recognition, wireless sensing

Abstract

Non-intrusive hand tracking with mmWave radar technology is important in various Human-Computer Interaction (HCI) scenarios. However, existing mmWave-based solutions require users to be stationary and restrict a fixed hand motion area, which limits application flexibility and user experience. This paper proposes a novel mmWave-based Mobile Hand Tracking (MHTrack) system, which tracks user's hand gestures during walking. MHTrack focuses on tracking both absolute hand trajectory in the global coordinate system and relative hand trajectory to the body. Specifically, we propose a wake-up mechanism for hand motion capture, in which hand point cloud can be recognized even under body interference and noise. We propose a hand tracking strategy named local spatial update, which overcomes the sparsity and instability of point clouds, to obtain absolute hand trajectory. Subsequently, we propose a hand anchor correction method to suppress anchor offset and remove the impact of body movement from absolute hand trajectory, thereby obtaining relative hand trajectory. As a case study, we project the relative hand trajectory onto a 2D image and feed it into a gesture recognition model to recognize the gestures. We conduct extensive experiments to evaluate the performance of MHTrack. Results demonstrate a 3D hand trajectory tracking error of 3.6 cm in an area of 3.2m×4.8m and a gesture recognition accuracy of 99% with 30 gesture classes.

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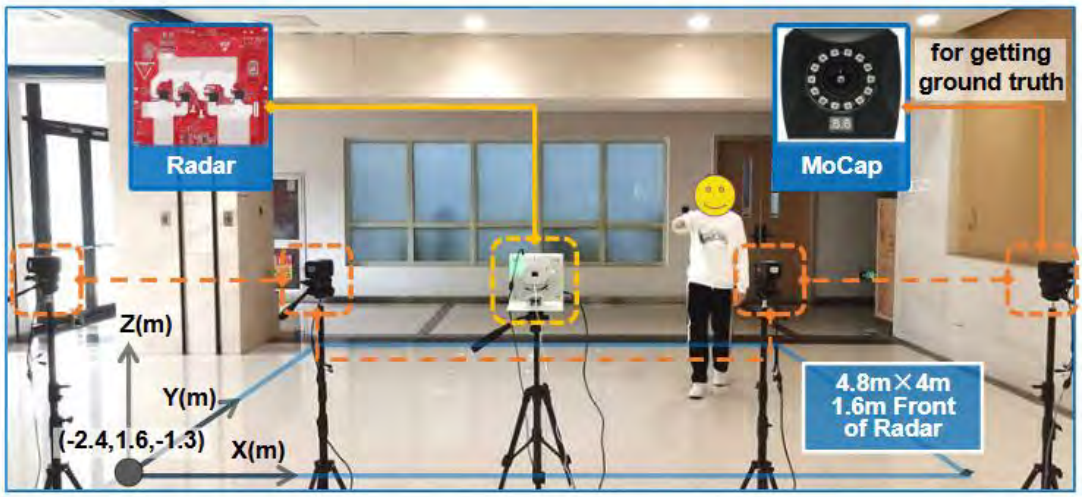

Fig. 10: Experimental environment.

How NOKOV Contributes to the Research

The data collection for the mmWave radar and MoCap is controlled by the official software, mmWave Studio and NOKOV, respectively. Subsequent data processing algorithms and network models are implemented through MATLAB R2022b and PyTorch, respectively.

Citation Liu X, Liu H, Han Y, et al. MHTrack: mmWave-based Mobile Hand Tracking[J]. IEEE Transactions on Mobile Computing, 2025.

Link https://ieeexplore.ieee.org/document/10962443

Model-independent pose estimation of non-cooperative targets based on sequential images and enhanced feature matching

Keywords

active debris, removal, space satellite, pose estimation, feature matching

Abstract

Non-cooperative targets pose estimation plays a vital role in close-range proximity operations for active debris removal and on-orbit servicing. However, model-independent approaches remain underexplored. Moreover, space targets, such as satellites, are covered with low-texture surface and repeated patterns, which also brings difficulties for visual-based feature matching. To address these challenges, we propose a model-independent approach to pose estimation tailored for non-cooperative targets (NCTs), which reconstructs a point cloud model and estimates the relative pose between the target and camera by matching 2D keypoints across sequential multi-view images. Considering the surface characteristics, we also combine the local feature matching and global context based mismatch removal, which greatly improves the quantity and quality of matches. To make up for the lack of datasets, a hybrid dataset comprising synthetic and hardware-in-the-loop images is created. The enhancement of our approach is validated through experiments on various scenarios.

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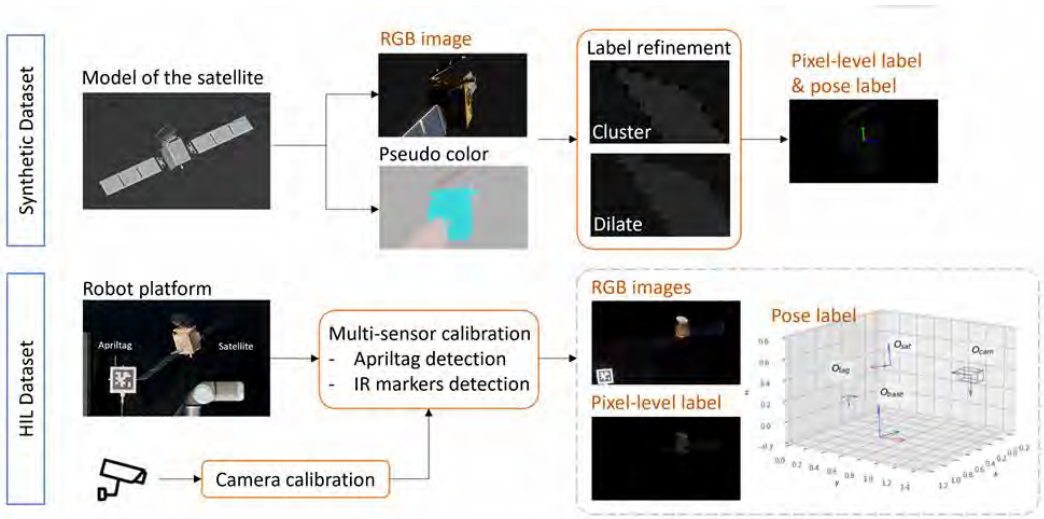

Figure 3: The illustration of the hybrid dataset. The synthetic RGB and labels are generated automatically. For HIL dataset, a multi-sensor calibration is designed to obtain the pose label. The pixel-level label are made by manual efforts.

How NOKOV Contributes to the Research

Since real space data is expensive, to provide data for network training and evaluate the pose estimation algorithm, a hybrid dataset with pixel-level semantic label and pose label is required. To build the dataset, an efficient strategy is designed as shown in Fig. 3. Synthetic images are rendered based on a realistic simulator. The pixel label of the component mask is first generated by the simulator and then refined to make it more accurate. The HIL images are collected by a calibrated camera on a robot-based platform. A multi-sensor calibration with Realsense visible camera and NOKOV Motion Capture System is proposed to calculate the pose label of the images.

Citation Zhu Y, Dong Z, Wang L, et al. Model-independent pose estimation of non-cooperative targets based on sequential images and enhanced feature matching[J]. Acta Astronautica, 2025.

Link https://www.sciencedirect.com/science/article/abs/pii/S0094576525003686

Modeling and Robust Adaptive Practical Predefined Time and Precision Tracking Control of Unmanned Fire Fighting Robot

Keywords

Modeling, predefined precision tracking, predefined time tracking, robust adaptive control, unmanned fire fighting robots (UFFRs)

Abstract

This article studies the modeling and tracking control problems for a class of towed unmanned fire fighting robots. Considering that no similar modeling results exist, we take the lead in building a novel system model that takes into consideration both system uncertainties and external disturbances, including unknown friction factors and drag force. Then, to compensate for the adverse effects of system uncertainties and external disturbances, a novel robust control algorithm is proposed, which utilizes adaptive control and scaling techniques. Moreover, innovative predefined performance functions are designed to ensure that tracking processes meet predefined transient and steady-state requirements. Unlike most of the existing works, our predefined time performance function has the advantage that the convergence time and convergence accuracy can be arbitrarily changed. In the end, a novel robust adaptive control scheme with predefined time and precision tracking is designed using the backstepping recursive method. Based on Lyapunov stability theory, it is demonstrated that all signals in the closed-loop system are ultimately bounded, and both predefined transient and steady-state processes are never violated. To validate the effectiveness of this proposed control scheme, numerical simulations and practical platform experiments have been conducted. To ensure repeatability, our codes are open sourced on Github: https://github.com/JiannanChen/Modeling-and-Robust-Control-UFFR.git.

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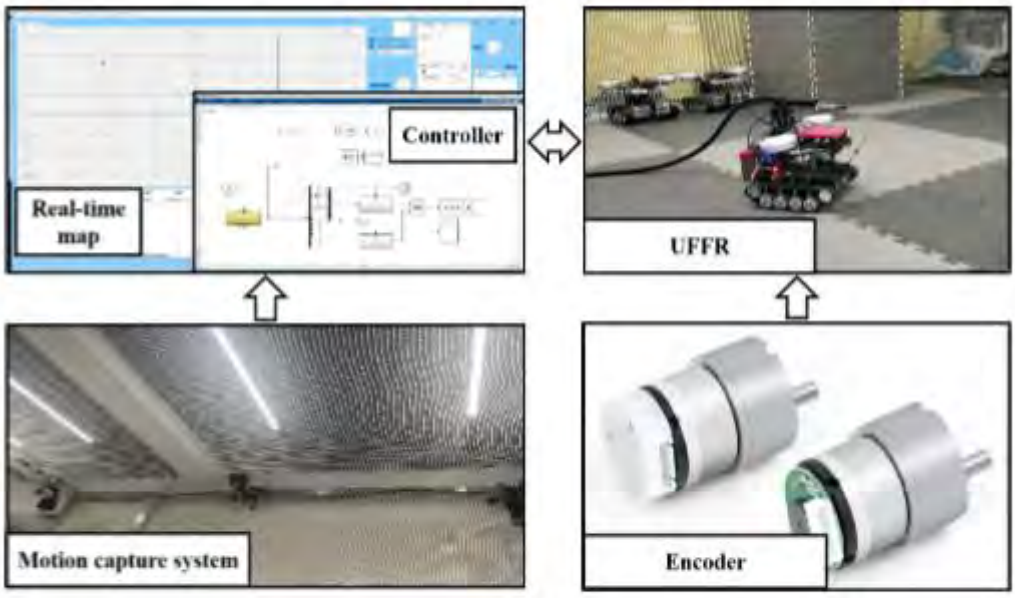

Fig. 5. System structure block diagram of our self-made unmanned fire fighting system platform.

How NOKOV Contributes to the Research

The operation process of the entire platform is shown in Fig.5:1) UFFR onboard STM32 uses PWM input capture mode to acquire the pulse number of the encoder unit, then the velocity of real-time calculating is transmitted to onboard Raspberry through serial communication, and further transmitted to MATLAB control unit through the network; 2) the position and attitude of the UFFR measured by the NOKOV motion capture system are transmitted to the MATLAB control unit through the network cable; 3) the MATLAB control unit receives these information to calculates the control signal according to the designed controller, and further sends it to the UFFR through the network with UDP protocol; and 4) in the end, the upper computer displays the UFFR trajectory in real time.

Citation Chen J, Luo X, Hua C, et al. Modeling and robust adaptive practical predefined time and precision tracking control of unmanned fire fighting robot[J]. IEEE Transactions on Systems, Man, and Cybernetics: Systems, 2024, 54(7): 4273-4283.

Link https://ieeexplore.ieee.org/abstract/document/10495058

Monocular-Vision-Based Relative Pose Estimation of Noncooperative Spacecraft Using Multicircular Features

Keywords

Monocular vision; multi circular features; non-cooperative target spacecraft; nonlinear optimization method; pose estimation.

Abstract

Accurate relative pose (position and orientation) estimation for non-cooperative target spacecraft is the basic module for on-orbit services, such as capture and repair. This article technically proposes a nonlinear optimization method based on monocular vision to estimate the relative pose for the solid-of-revolution-shaped nonco- operative spacecraft. Specifically, considering the multi circular features on the target, the parameters of the ellipses derived from the circles perspective projection are first obtained by the propounded ellipse detection algorithm. Moreover, the constraint that the center of each circle falls on the center axis (normal direction) of the spacecraft is utilized to optimally solve the center position and the normal of the multi circles. In particular, the roll angle around the center axis is recovered through the geometric constraints of the solar panels, and the six-degree-of-freedom spacecraft pose estimation is then accomplished. Consequently, it is analyzed that the proposed optimization algorithm is able to provide a closed-form solution to ensure the accuracy of the relative pose and only requires limited computational resources. Finally, experimental results on the synthetic images and the physical scenes are conducted to evaluate the efficiency of the proposed approach.

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How NOKOV Contributes to the Research

The noncooperative target spacecraft model is Shenzhou 12, and the Nokov motion capture system is used to obtain the ground truth pose of the noncooperative target relative to the camera.

Citation Long C, Hu Q. Monocular-vision-based relative pose estimation of noncooperative spacecraft using multicircular features[J]. IEEE/ASME transactions on mechatronics, 2022, 27(6): 5403-5414.

Link https://ieeexplore.ieee.org/abstract/document/9802504

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Multi-Target Encirclement with Collision Avoidance via Deep Reinforcement Learning using Relational Graphs

Abstract

In this paper, we propose a novel decentralized method based on deep reinforcement learning using robot-level and target-level relational graphs, to solve the problem of multi-target encirclement with collision avoidance (MECA). Specifically, the robot-level relational graphs, composed of three heterogeneous relational graphs between each robot and other robots, targets and obstacles, are modeled and learned through using graph attention networks (GATs) for extracting different spatial relational representations. Moreover, for each target within the observation of each robot, a target-level relational graph is built with GAT to construct spatial relations from the robot. Furthermore, the movement of each target is modeled by the target-level relational graph and learned through supervised learning for predicting the trajectory of the target. In addition, a knowledge-embedded compound reward function is defined to solve the multi-objective problem in MECA, and guide the policy learning for deriving the behavior of MECA. An actor-critic training algorithm based on the centralized training and decentralized execution framework is adopted to train the policy network. Simulation and real-world experiment results demonstrate the effectiveness and generalization of our method.

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How NOKOV Contributes to the Research

Aside from the simulations above, we also examine the trained policy in real-world experiments on an experimental platform based on omnidirectional robots. In the experimental platform, each robot is equipped with an onboard computer (Nvidia Jetson TX2) to improve the real-time performance of policy implement. Moreover, the positions and velocities of the robots are provided by the NOKOV motion capture system. The three snapshots of 6 robots encircling 2 targets in 2 obstacle environment are presented in Fig. 4. These actual results show the robots can successfully complete the MECA task, which demonstrates the effectiveness and practicability of the proposed method.

Citation Zhang T, Liu Z, Pu Z, et al. Multi-target encirclement with collision avoidance via deep reinforcement learning using relational graphs[C]//2022 International conference on robotics and automation (ICRA). IEEE, 2022: 8794-8800.

Link https://ieeexplore.ieee.org/abstract/document/9812151

OTPS-VO: Enhanced RGB-D odometry for indoor service robots leveraging structural features

Keywords

Service robot, SLAM, Visual odometry, Geometric structure, Structural line feature

Abstract

Simultaneous Localization and Mapping (SLAM) is essential for indoor service robots to achieve reliable navigation and mapping. While point and line features have been extensively utilized to enhance the accuracy of visual odometry (VO), current methods often overlook the rich geometric information embedded in the spatial relationships among structural lines. In particular, the parallelism and collinearity within groups of line segments are underexploited, and geometric constraints are typically applied only heuristically or post hoc, limiting robustness in low-texture and repetitive environments. To address these challenges, a robust VO system is proposed that integrates structural feature grouping with adaptive MW tracking. A unified feature extraction strategy is introduced to detect point and line features simultaneously, improving computational efficiency. To mitigate pose drift caused by unreliable line segments, a set of parallel line features is constructed based on local geometric constraints, and a novel reprojection error model is formulated to enhance pose estimation. Furthermore, a tracking strategy based on local Manhattan World (MW) structure is developed to ensure low-drift estimation across various structured indoor scenes. Extensive experiments on multiple public datasets and a custom-built service robot platform demonstrate that the proposed method outperforms existing state-of-the-art approaches under dynamic lighting conditions and in environments rich in lines and planes. The system also operates at a real-time speed of 30 frames per second, meeting the requirements of practical robotic applications.

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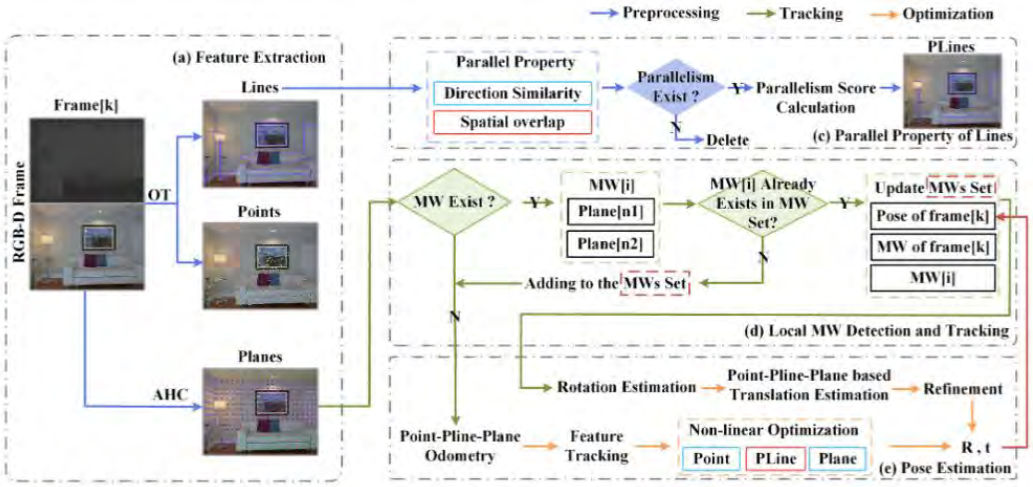

Fig. 1. Overview of the proposed RGB-D odometry framework. Module (a) extracts point, line, and plane features from each frame. Module (c) groups line features into parallel structures. Module (d) constructs and tracks local Manhattan World (MW) structures using planar features, enabling robust rotation estimation when reliable MW hypotheses are available. Module (e) estimates full camera poses by jointly optimizing point, line, and plane constraints. Modules (d) and (e) run in parallel. The red box highlights the key differences from existing methods. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

How NOKOV Contributes to the Research

In the home environment, the scene consists of multiple inter.connected indoor regions featuring everyday furniture and objects. It includes desks with various items such as laptops, cups, plants, and decorations, as well as bookshelves, cabinets, and storage boxes. The layout presents a structured environment with a combination of flatsurfaces, vertical planes, and scattered structural lines, providing are alistic domestic scenario for testing visual odometry systems. To obtain accurate ground truth trajectories, a NOKOV metric motion capture system was used. The accuracy and drift of the proposed algorithm in real-world settings were assessed using the ATE and RPE met.rics. The final mapping results were also visually evaluated. The experimental results, as shown in Table 8, indicate that the proposed VOachieved the best performance in terms of pose estimation accuracy However, due to the relatively simple home environment with fewer structural line features, the results were close to those of ORBSLAM3. In contrast, WSLAM exhibited unstable drift during robot turns due to the presence of multiple planes, leading to a decrease in accuracy. From the perspective of accuracy and stability, the proposed VO demonstrated the smallest RMSE values in both ATE and RPE metrics. Despite this, the small scale and short trajectory of the home environment resulted in similar drift levels among the three algorithms. Fig. 18 visually com-pares the 3D tracking trajectories and final mapping results of the three algorithms, clearly showing that the proposed VO method out performed the others in terms of trajectory estimation and mapping quality. While the home scenario demonstrates the algorithm's competitiveness in relatively simple structured environments, its advantages become more evident when moving to more complex and cluttered office environments.

Citation Wang Z, Ding W, Zhang Y, et al. OTPS-VO: Enhanced RGB-D odometry for indoor service robots leveraging structural features[J]. Expert Systems with Applications, 2026, 298: 129704.
Link https://www.webofscience.com/wos/woscc/full-record/WOS:001574122900001

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Point feature correction based rolling shutter modeling for EKF-based visual-inertial odometry

Keywords

rolling shutter camera,visual inertial odometry (VIO), self-calibration, observability, simultaneous localization and mapping(SLAM)

Abstract

The application of consumer-grade rolling-shutter (RS) cameras in visual inertial odometry (VIO) systems deserves attention. In previous works, VIO systems with RS cameras usually adopt different dimensions of RS modeling to represent the camera motion. Although the complex camera motion expression improves accuracy, adding more variables greatly increases the computation load. Therefore, considering the limitations of camera motion modeling, this paper introduces a point feature correction strategy to improve the performance of the system in terms of both speed and accuracy. The optimized camera poses and high-frequency inertial measurement unit (IMU) are employed to correct the point features in the RS image to new pixel coordinates in the global shutter view (in the middle of the RS image readout time) by epipolar transfer. At the same time, we handle the zero velocity and abnormal cases of RS modeling to improve the robustness of the system. Furthermore, the readout time of the RS camera is self-calibrated online during the state augmentation stage and can quickly converge and stabilize to near the true value. The readout time of the RS camera is locally observable, except for two degenerate motions. Experimental results demonstrate that the proposed method outperforms the state-of-the-art methods on a public dataset in terms of accuracy and computational cost. We port our algorithm to an Android-based mobile phone and our system outputs real-time trajectories on the mobile phone. Then, we use the motion capture system to obtain the ground truth phone pose to test the performance of our algorithm.

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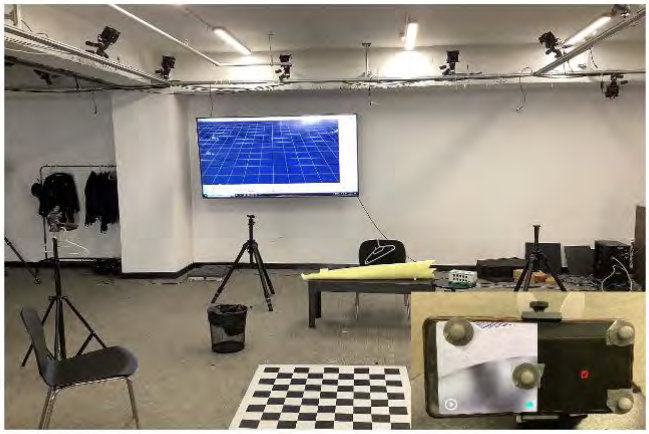

Figure 9. Indoor environment with the Nokov motion capture system. The bottom right corner of the picture is the mobile phone marked by markers.

How NOKOV Contributes to the Research

To further evaluate the proposed method under more challenging real-world scenarios, we port our system to a mobilephone (Huawei)which contains a camera (640 x 480.25 Hz)and IMU (250 Hz). The ground-truth motion is recorded with a Nokov motion capture system, as shown in figure 9.

Citation Zhang K, Zhang M. Point feature correction based rolling shutter modeling for EKF-based visual-inertial odometry[J]. Measurement Science and Technology, 2023, 35(1): 015133.

Link https://iopscience.iop.org/article/10.1088/1361-6501/ad044e

Quantifying Uncertainties in Nonlinear Dynamics of a Modular Assembly Using the Resonance Decay Method

Keywords

uncertainty quantification; large structure assembly; resonance decay method

Abstract

Modular assembling is a promising approach to constructing large spacecraft beyond the size limitations posed by launch vehicles. However, the uncertainties and nonlinearities of the dynamics associated with the assembled structure are deeply concerned in the design stage of such spacecraft. Conventionally, this concern can be relieved by performing Ground Vibration Testing (GVT) of the structure. Nevertheless, it is challenging for a modular assembly, among which its very-low frequency behaviour and a lack of dynamic testing procedure that can incorporate with nonlinearities are two major obstacles. In this regard, the present paper firstly introduces a demonstrator for Large Structure Assembly (LSA demonstrator), which includes a soft-bungee suspension system, a 6-meter-long modular assembly, a vibration control system, and a non-contact measurement system. Secondly, a new quantification procedure for modular assembly, which utilises the resonance decay method, was proposed in this paper. Detailed test steps were illustrated through the demonstrator, in which the backbone curves were treated as key measurement targets in quantifying its nonlinear dynamics. The uncertainties in nonlinear dynamics were also evaluated by assembling and disassembling the structure multiple times. Results have shown that the proposed procedure can efficiently and accurately quantify the dynamics of a highly-flexible, large-scale modular assembly.

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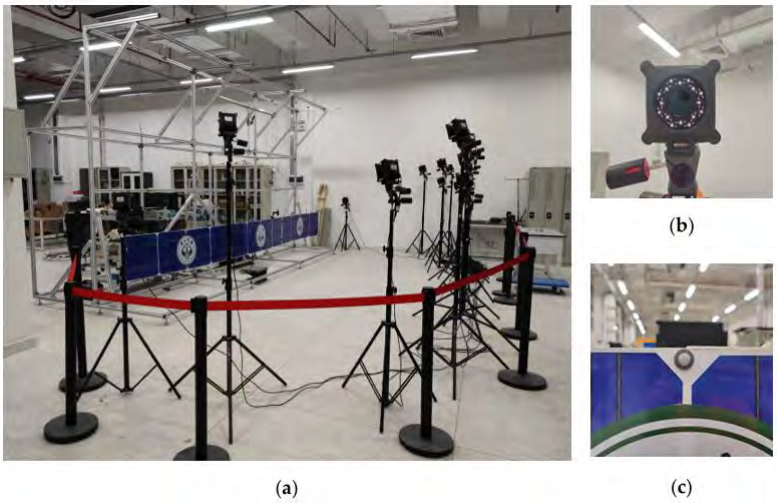

Figure 5. The measurement system: (**a**) overview of the non-contact motion capture system, (**b**) camera lens and (**c**) reflective marking points attached to the test structure.

How NOKOV Contributes to the Research

Considering the very-low natural frequencies of the modular assembly predicted in Table 1, a non-contact motion capture system (NOKOV) was established to perform 3D dynamic displacement measurements. As shown in Figure 1, a total of 18 passive markers were distributivity attached to the modular assembly as measurement targets and 14 cameras were installed approx. 5 meters away from the structure (see Figure 5). The NOKOV system tracked these markers simultaneously by infrared light and calculated 3D coordinates of each marker with images from at least two cameras.

Citation Lin, C.; Zhao, Z.; Wang, Z.; Jiang, J.; Wu, Z.; Wang, X. Quantifying Uncertainties in Nonlinear Dynamics of a Modular Assembly Using the Resonance Decay Method. Actuators 2022, 11, 350. https://doi.org/10.3390/act11120350

Link https://www.mdpi.com/2076-0825/11/12/350

Robust Tracking Model Predictive Control With Quadratic Robustness Constraint for Mobile Robots With Incremental Input Constraints

Keywords

Incremental input constraint, model predictive control (MPC), wheeled mobile robots (WMRs)

Abstract

This article proposes a robust model predictive control (MPC) algorithm for the tracking problem of wheeled mobile robots. The robots are subject to bounded disturbances and various practical constraints. Particularly, the incremental input constraint is introduced in the consideration of the safety and comfortability needs in real life. Conditions on the acceleration of the leader robot are derived to guarantee the satisfaction of the incremental input constraint of follower robot. To compensate for the effect of disturbances, a disturbance observer is designed to obtain the estimation of the disturbances, which together with the optimal control input of MPC optimization is contained in the actual control input. Also, a novel quadratic robustness constraint is developed to handle the disturbance estimation error, which allows the designer to balance the initial feasible region and control performance. The proposed algorithm can ensure recursive feasibility, robust constraint satisfaction, and closed-loop stability. Finally, both simulation and experiment results are provided to verify the theoretical properties.

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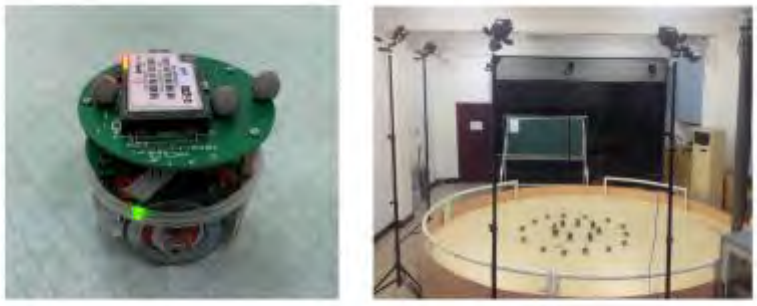

(a) (b)

Fig. 7. (a) E-puck wheeled mobile robot. (b) Experiment platform with NMCS.

How NOKOV Contributes to the Research

Besides, the experiment platform has a Nokov motion capture system (NMCS) which is made of eight cameras to real-time capture and record the kinematics information of robots. Considering the computation load of MPC, the optimal control input is calculated on PC offline, then send the control signal and state information by Wi-Fi network to the WMRs.

Citation Dai L, Lu Y, Xie H, et al. Robust tracking model predictive control with quadratic robustness constraint for mobile robots with incremental input constraints[J]. IEEE Transactions on Industrial Electronics, 2020, 68(10): 9789-9799.

Link https://ieeexplore.ieee.org/document/9209064

Safe and Efficient Multi-Agent Collision Avoidance With Physics-Informed Reinforcement Learning

Keywords

Reinforcement learning (RL), path planning for multiple mobile robots or agents, collision avoidance

Abstract

Reinforcement learning (RL) has shown great promise in addressing multi-agent collision avoidance challenges. However, existing RL-based methods often suffer from low training efficiency and poor action safety. To tackle these issues, we introduce a physics-informed reinforcement learning framework equipped with two modules: a Potential Field (PF) module and a Multi-Agent Multi-Level Safety (MAMLS) module. The PF module uses the Artificial Potential Field method to compute a regularization loss, adaptively integrating it into the critic's loss to enhance training efficiency. The MAMLS module formulates action safety as a constrained optimization problem, deriving safe actions by solving this optimization. Furthermore, to better address the characteristics of multi-agent collision avoidance tasks, multi-agent multi-level constraints are introduced. The results of simulations and real-world experiments showed that our physics-informed framework offers a significant improvement in terms of both the efficiency of training and safety-related metrics over advanced baseline methods.

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TABLE III
RUNNING TIME PER STEP OF THE MAIN COMPONENTS

Phase	Total	Network Learning	Environment Transition	MAMLS
Train (s)	0.035 ± 0.005	0.012 ± 0.002	0.023 ± 0.004	0.004 ± 0.003
Execution (s)	0.025 ± 0.006	/	0.025 ± 0.005	0.004 ± 0.003

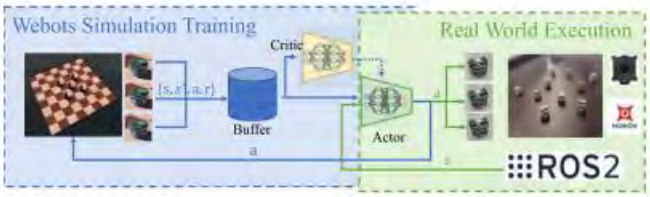

Fig. 10. Structure of the e-puck swarm platform.

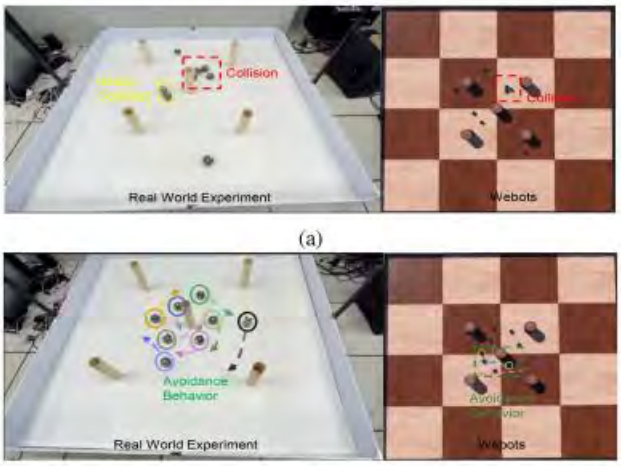

Fig. 11. Two representative scenarios: (a) Collision with BHDQN. (b) Collision avoidance using our method.

How NOKOV Contributes to the Research

As is shown in Fig.10, we verified the applicability of our policies to practical scenarios through hardware experiments one-puck swarms, by using the NOKOV motion capture system for indoor positioning. Fig.11shows two representative scenarios where our method surpassed baselines, achieving the shortest travel distances without collisions.

Citation Feng P, Shi R, Wang S, et al. Safe and efficient multi-agent collision avoidance with physics-informed reinforcement learning[J]. IEEE robotics and automation letters, 2024.

Link https://ieeexplore.ieee.org/document/10737374

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TACO: Benchmarking Generalizable Bimanual Tool-Action-Object Understanding

Keywords

Computer vision; Three-dimensional displays; Codes; Pipelines; Data acquisition; Benchmark testing; Motion capture; Dataset; Hand-object Interaction; Motion Synthesis; Action Recognition; Motion Capture

Abstract

Humans commonly work with multiple objects in daily life and can intuitively transfer manipulation skills to novel objects by understanding object functional regularities. However, existing technical approaches for analyzing and synthesizing hand-object manipulation are mostly limited to handling a single hand and object due to the lack of data support. To address this, we construct TACO, an extensive bimanual hand-object-interaction dataset span-ning a large variety of tool-action-object compositions for daily human activities. TACO contains 2.5K motion se-quences paired with third-person and egocentric views, pre-cise hand-object 3D meshes, and action labels. To rapidly expand the data scale, we present a fully automatic data acquisition pipeline combining multi-view sensing with an optical motion capture system. With the vast research fields provided by TACO, we benchmark three generalizable hand-object-interaction tasks: compositional action recognition, generalizable hand-object motion forecasting, and cooperative grasp synthesis. Extensive experiments reveal new insights, challenges, and opportunities for advancing the studies of generalizable hand-object motion analysis and synthesis. Our data and code are available at https\://taco2024.github.io.

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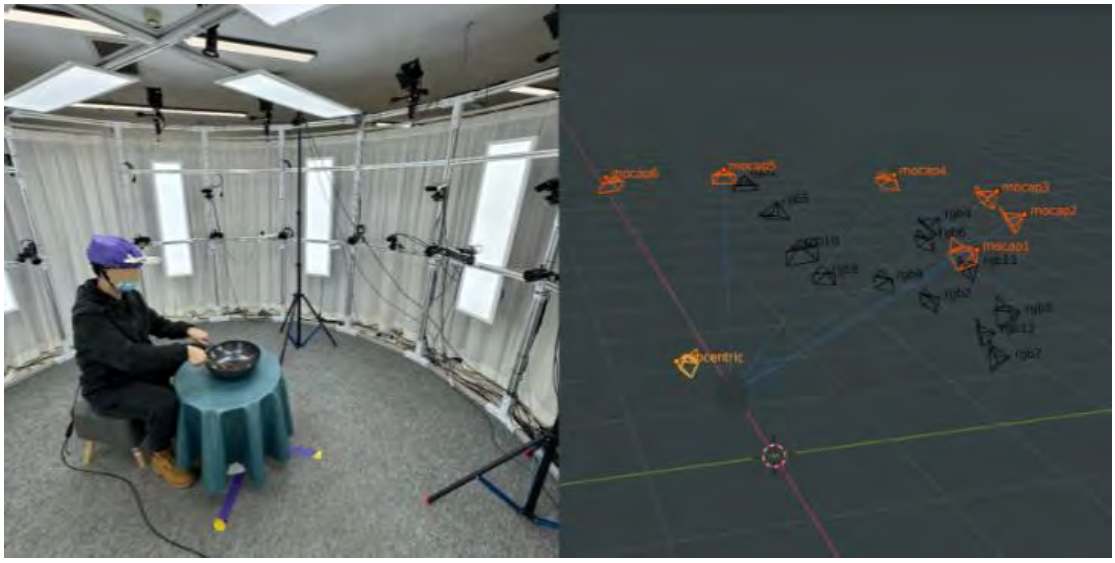

How NOKOV Contributes to the Research

Our data capturing system incorporates 12 synchronized industrial FLIR cameras and a NOKOV optical motion capture suite with 6 infrared Mars4H cameras. NOKOV optical motion capture suite is utilized to capture the object motion.

Citation Liu Y, Yang H, Si X, et al. Taco: Benchmarking generalizable bimanual tool-action-object understanding[C]//Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition. 2024: 21740-21751.

Link
https://openaccess.thecvf.com/content/CVPR2024/html/Liu_TACO_Benchmarking_Generalizable_Bimanual_Tool-ACtion-Object_Understanding_CVPR_2024_paper.html

Towards validated dynamic models for tensegrity structures: Parametric modelling, vibration testing, and model updating of a hexagonal prism

Keywords

Tensegrity structure, Sensitivity analysis, Experimental modal analysis, Finite element model updating

Abstract

Tensegrity structures are self-equilibrium systems connected by compression rods and tension strings. They represent a promising structural type in aerospace applications due to the light-weight advantage. Conventional transducers, such as accelerometers, are difficult to apply to the rods or strings, making it challenging to measure the dynamic behaviours of tensegrity structures. It has hindered model updating studies and the accurate modelling of these structures, which are of great interest from an industrial point of view. Additionally, state-of-the-art model updating methods, which routinely adjust parameters such as geometric dimensions or elastic modulus for engineering structures, may be inadequate to apply to a tensegrity structure, as its structural stiffness depends on both material properties and prestress in rods and strings. To address these challenges, this paper presents a systematic approach towards validated dynamic models for tensegrity structures. First, a parametric finite element (FE) model is established, and sensitivity analyses of nodal positions, elastic modulus and prestress levels on the natural frequencies of the prism are carried out. Numerical simulations show that the prestress level is a critical factor that affects its natural frequencies. Second, full-field vibration testing of the prism is carried out. A single-point excitation is employed to obtain the frequency response functions, from which three natural frequencies and modal damping ratios are identified. Next, full-field mode shapes of the prism are measured by dwelling the excitation at each of the identified natural frequencies and tracking the full-field vibrations using a non-contact motion capture system. Third, a novel model updating method for tensegrity structures is proposed by utilising the test results. The measured full-field mode shapes are paired with those FE predictions using a modified cross-modal assurance criterion (cross-MAC), with special treatment to account for degenerated modes attributed to the symmetry of the structure. Subsequently, the test/analysis discrepancies of the natural frequencies for the paired modes are minimised by adjusting the

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prestress levels of strings in the FE model. As shown by the results, the updating process effectively reduces the test/analysis discrepancies of the natural frequencies from 29.2 % to 5.3 %. It also estimates the prestress values as 18.54 N and 22.01 N for the horizontal and diagonal strings, respectively. Finally, direct tension measurements of the strings are carried out as a validation tool for the proposed model updating method. Discrepancies in the prestress levels of the strings, ranging from 13.44 % to 27.72 %, confirm the feasibility of the proposed method. The parametric model, experimental data, and model updating codes are openly available to serve as a benchmark for accurate modelling of tensegrity structures.

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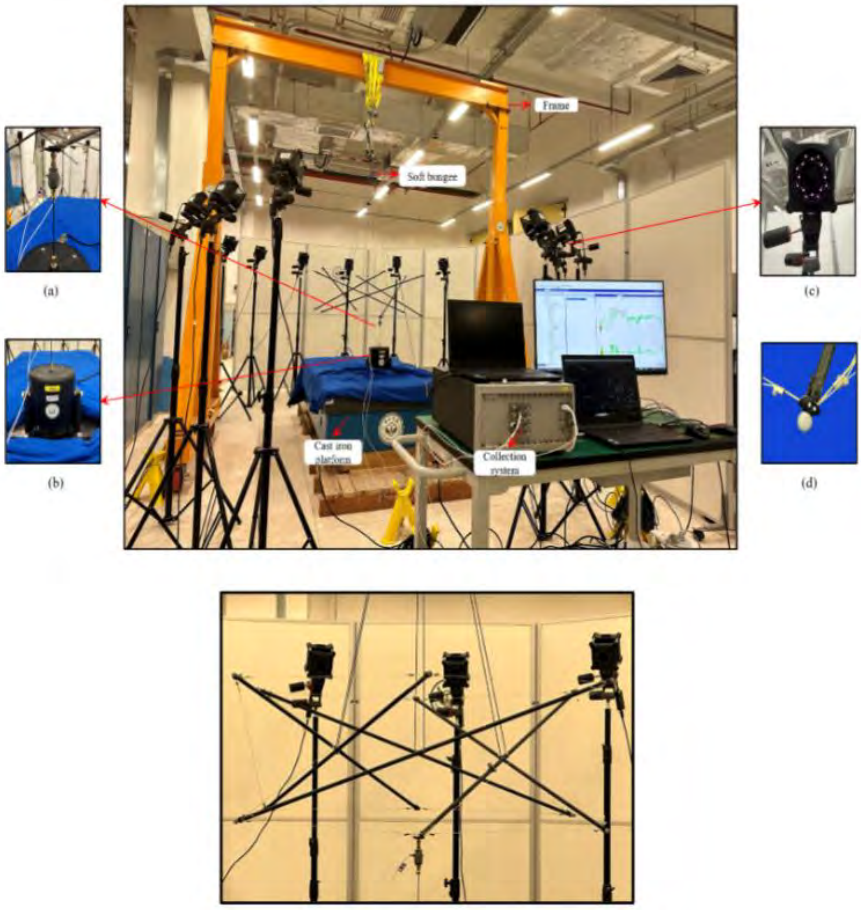

Fig. 11. Test setup for the hexagonal prism tensegrity: (a) carbon fibre stinger and impedance head; (b) shaker; (c) camera lens; (d) reflective markers attached to the test structure; (e) zoom-in view of the hexagonal prism tensegrity.

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How NOKOV Contributes to the Research

Vibration testing strategy
Test setup
Fig. 11 provides an overview of the test setup used for experimental modal analysis of the hexagonal prism tensegrity. The test setup for the hexagonal prism tensegrity includes several key components. Fig. 11(a) displays the flexible carbon fibre stinger and impedance head (Kistler 8770A) used to connect the vibration exciter to the structure. The stinger serves to transmit the excitation force from the shaker to the test article, and the impedance head measures both the axial force (sensitivity 22.67 mV/N) applied and the collocated acceleration (sensitivity 94.7 mV/g). Fig. 11(b) shows an electrodynamic shaker (DONGHUA DH40200), driven by a HEA.200C power amplifier, mounted on a cast iron platform. Fig. 11(c) highlights the NOKOV non-contact motion capture cameras used to measure 3D dynamic displacements. Twelve cameras are installed approximately 2.5 m from the structure. As shown in Fig. 11(d), all the end fittings of the hexagonal prism tensegrity have reflective markers attached, serving as measurement targets. The cameras use infrared light to track these markers simultaneously, and the 3D coordinates of each marker are calculated from images captured by at least two cameras. Fig. 11(e) shows the hexagonal prism tensegrity suspended by a soft bungee system attached to a rigid frame, simulating "free-free" boundary conditions. Additionally, the setup includes a Siemens LMS CADAS II system, which generates signals for the shaker as well as samples data from the impedance head. We employed the Random Control module in the LMS Test.Lab to create the excitation signals and the SCADAS Recorder module to capture force and acceleration data from the impedance head.

Citation Huang K, Zhao Z, Lin C, et al. Towards validated dynamic models for tensegrity structures: Parametric modelling, vibration testing, and model updating of a hexagonal prism[J]. Journal of Sound and Vibration, 2025: 119350.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001570624000001

Tuning responsivity-persistence trade-off in swarm robotics: A motion salience threshold approach

Keywords

Swarm robotics, Collective behavior, Responsivity-persistencet rade-off, Motionsalience

Abstract

In swarm robotics, balancing two crucial properties is essential: responsivity, which enables quick reactions to environmental changes, and persistence, which maintains stable goal-directed behavior despite distractions. Responsivity is necessary for tasks like evading obstacles or responding to threats. In contrast, persistence is key to ensuring coordinated movement and focus on long-term goals, such as migration or search missions. To address the challenge of balancing these conflicting properties, we introduce the Motion Salience Threshold (MST). This approach enables swarm robots to selectively respond to significant motion cues, thereby enhancing overall system performance by minimizing unnecessary reactions to less critical changes. This tuning mechanism is particularly useful in real-world applications where the environment is unpredictable and demands both flexibility and stability from the robotic swarm. Our research demonstrates that lower threshold values increase responsivity, enabling the swarm to react quickly in highly dynamic environments, whereas higher values bolster persistence, reducing the impact of false positive signals and maintaining focus on long-term goals. The proposed approach offers a targeted method for fine-tuning swarm behavior, validated through extensive simulations and real-world experiments with robotic systems. These findings provide valuable insights for designing adaptive robotic swarms that can navigate complex and unpredictable environments more effectively.

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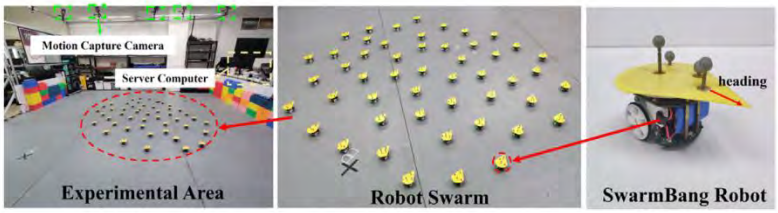

Fig. 4. The SwarmBang system. Experiments were conducted in a 5000 mm × 6000 mm area with 50 robots and a NOKOV motion capture system.

How NOKOV Contributes to the Research

As shown in Fig.4,we conducted experiments in a 5000 mm x 6000 mm area using the SwarmBang system. The SwarmBang system includes up to 102 table-level robots and a NOKOV motion capture system.
The NOKOV motion capture system captures the positions and headings of all robots. The server computer calculates the desired velocities for each robot based on the model and broad casts these velocities to the robots at fixed intervals using a custom communication protocol. The robots then adjust their linear and angular velocities according to the received desired velocities.

Citation Li Y, Zheng Z, Xiang Y, et al. Tuning responsivity-persistence trade-off in swarm robotics: A motion salience threshold approach[J]. Robotics and Autonomous Systems, 2025: 105055.

Link https://www.sciencedirect.com/science/article/abs/pii/S0921889025001411

Two-dimensional viscoelastic beam element for ultra-large space structures based on absolute nodal coordinate formulation

Keywords

Viscoelastic beam, absolute nodal coordinate formulation, large space structure, rigid-flexible coupled system, Kelvin-Voigt damping

Abstract

Internal damping is an important factor in the dynamic behaviors of ultra-large space structures in zero damping space environment. To precisely describe the damping, this paper proposes a two-dimensional viscoelastic Euler-Bernoulli beam element based on absolute nodal coordinate formulation and Kelvin-Voigt damping model, where the damping stress is linearly dependent on the stress rate. Firstly, a precise generalized damping force model is developed using the principle of virtual work. A simplified generalized damping force model is then proposed to improve simulation efficiency by neglecting the axial damping force and a part of the transverse damping force. Numerical simulations show that the proposed damping force models will not affect the rigid-body motion of the beam. Then, a simple formula is presented to estimate the damping ratio of the beam for different parameters, which shows good agreement with the logarithmic decrement method in simulations. Finally, the effects of viscoelastic damping on the dynamic behaviors of a Sun-facing beam in space are investigated. Simulation results reveal that the viscoelastic damping can greatly reduce the vibration amplitude of the beam near the resonance frequencies.

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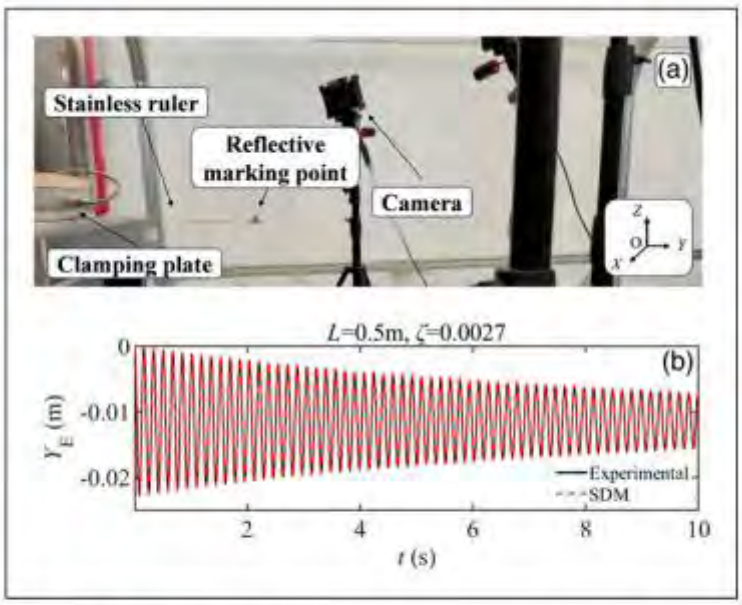

Figure 8. Comparison between experimental result and SDM: (a) Experimental system and (b) vibrations of Point E of ruler-1 in 0.5 m.

How NOKOV Contributes to the Research

A reflective marking point is placed on the end of the ruler for a high-precision noncontact motion capture system(NOKOV) to localize the position of the endpoint. The dis-placement of the endpoint of the ruler in the normal direction is measured by four cameras of the motion capture system.

Citation Jiang G, Jiang J, Yang G, et al. Two-dimensional viscoelastic beam element for ultra-large space structures based on absolute nodal coordinate formulation[J]. Journal of Vibration and Control, 2024, 30(21-22): 4814-4827.

Link https://journals.sagepub.com/doi/abs/10.1177/10775463231214292

Visual-inertial odometry based on point transfer correction

Abstract

Due to the low motion efficiency and maneuver-ability of underwater robots with six degrees of freedom, it is challenging for them to respond quickly to the attitude requirements during underwater autonomous manipulation. This paper presents a novel autonomous underwater robot with fully vectored propulsion and a model predictive control method to achieve more agile and efficient movements autonomously. In detail, we first design a robot with eight vector-distributed thruster layouts for fully vectored propulsion and construct the software architecture based on the robot operating system (ROS). Then, we establish the hydrodynamic model by adopting the Fossen approach and construct a 13-dimensional system state-space equation, which is discretized using the explicit fourth-order Runge-Kutta method. To achieve autonomous manipulation, model predictive control is employed along with physical constraints of the custom-built robot to enable real-time prediction and optimization of the robot's states for control purposes. Finally, numerical simulations and experiments of the Point-to-Point Motion are conducted to test the robot's performance. Experimental results reveal that the average error of each direction is 0.0027 m, 0.0031 m, and 0.0368 m in the x-axis, y-axis, and z-axis, respectively, and 0.8502°, 2.1941°, 0.2408° corresponding to three attitude angles, which verify the performance of employing MPC to control an autonomous underwater robot with fully vectored propulsion.

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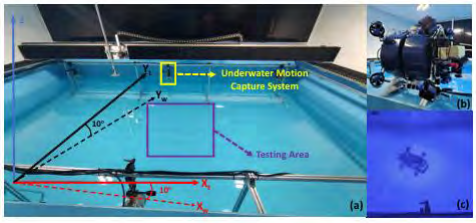

How NOKOV Contributes to the Research

The experiment was conducted in a 5 m × 3m × 1.5mindoorrectangular tank, surrounded by a set of NOKOV Motion Capture System with six underwater cameras, and the sampling rate of the system is 100 Hz.

Citation 张梦龙,张凯杰,刘昌林等.基于点转移矫正的视觉惯性里程计[J].中国惯性技术学报,2024,32(02):146-152.DOI:10.13695/j.cnki.12-1222/o3.2024.02.006.

Link https://kns.cnki.net/kcms2/article/abstract?v=6RIcORkFSJSrvOeaDTcUYzoc-t5oRrKKj0Ffc2AiwFWhNvantn702qbgWaooYBEM739cn2FIuFIHdxztPM89GLrantFRvZe61qxg_HI4mN9wSTvC66mgk6LUBX5x7rLG&uniplatform=NZKPT&language=gb

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3D-printed chiral-based systems with reprogrammable stiffness for mechanical logics via inter-unit interactions

Keywords

Chiral structures; metamaterials; mechanical computing; additive manufacturing; structural design

Abstract

Even if mechanical computing can supplement semiconductor-based digital logic in demanding circumstances, it still requires reprogrammable devices to effectively change computing rules. We propose an approach predicated on chiral structures with suitable compression-twist behaviour and continuously tuneable stiffness, which processes digital information through their interactions. The chiral units are, in fact, used as electrical switches to enable logic calculations in response to environmental stimuli. Two basic chiral structures create a buffer and a NOT gate; when combined adequately in multi-unit embodiments, they can form fundamental gates (AND, OR, NAND, NOR, XOR and XNOR) and advanced combinational logic systems. Corresponding finite element analyses and experimental validations clarify how to achieve reprogrammable stiffness via inter-unit interactions and confirm the applicability of this methodology. Thus, this reprogrammable metamaterial expands the design space for integrated mechanical systems, supporting the development of mechanical computing.

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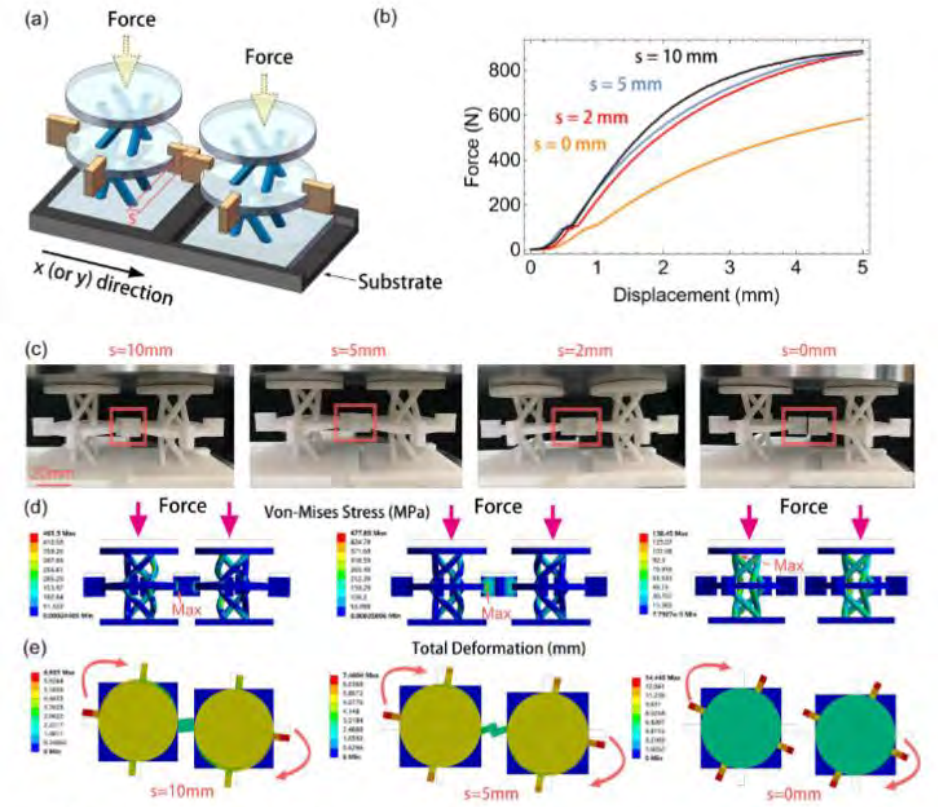

Figure 2. Reprogrammable stiffness of the system comprising two units. (a) Visualisation of two units and their substrate, with the indication of the overlap distance s. (b) Measured force-displacement curves with $s = 10$, 5, 2, and 0mm, and $d_m = 20$ mm, and (c) Corresponding photographs of the two-unit assemblies. Resulting (d) von Mises stress in the two units and (e) deformation under a 5 mm compression.

How NOKOV Contributes to the Research

2.3. Mechanical properties of the chiral structures
To characterise the behaviour of our chiral design, we measured the twisting angle of the intermediate plate when the unit rotates. We tracked the motion of two spherical tracers with a 3 mm diameter fixed to the top edges of the vertical panels using the motion capture system NOKOV MARS2H (Beijing, China) with six cameras. This device recognises the reflected infrared radiation of the tracers and calculates the tracer positions, namely, the points i=1 and 2. It employs a 2D reference system by projecting onto a plane the points i at the time instant t giving the coordinates Xi (t), and that at the instant t+Δt leading to the coordinates Xi (t+Δt) .

Citation Yang N, Luo J, Lan Y, et al. 3D-printed chiral-based systems with reprogrammable stiffness for mechanical logics via inter-unit interactions[J]. Virtual and Physical Prototyping, 2026, 21(1): e2650248.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001734993900001

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An improved NExT-DMD for efficient automated operational modal analysis

Keywords

Automated operational modal analysis; Dynamic mode decomposition; DBSCAN; Natural excitation technique; Closely spaced modes

Abstract

The demand for identifying modal parameters under random excitation is rapidly increasing, but improving the efficiency of automated operational modal analysis (AOMA) remains a significant challenge, particularly during the time-consuming system identification stage. We propose an efficient AOMA method based on the integration of the natural excitation technique (NExT) with dynamic mode decomposition (DMD), termed as NExT-DMD, coupled with the density-based spatial clustering of applications with noise (DBSCAN). This improved NExT-DMD overcomes the reliance of original DMD on free-decay responses and allows operational modal analysis, i.e. modal parameter identification from random excitations. A systematic hyperparameter optimization strategy for DBSCAN is developed based on rank stability, facilitating automated identification. A numerical composite wing model with closely spaced modes was used to validate the proposed method, demonstrating a maximum frequency difference of 3.43 % against the finite element method. With the responses captured by the non-contact three-dimensional optical technique, a physical wing model was tested to show the capability of the proposed method to deal with real-world complex structures. The results demonstrate that our method can improve the identification efficiency by 41.10 % compared with the NExT-eigensystem realization algorithm (ERA) and by 53.83 % compared with covariance-driven stochastic subspace identification (Cov-SSI). The efficient NExT-DMD AOMA method is promising for operational modal analysis with large datasets.

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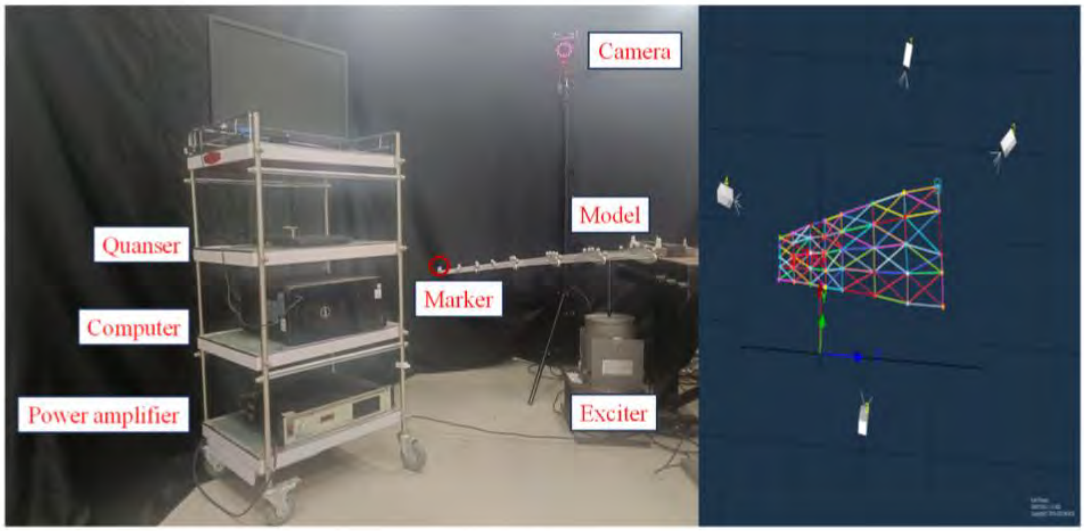

Fig. 11. Experimental setup, geometric model, and camera position in NOKOV motion capture system.

How NOKOV Contributes to the Research

A noncontact vibration measurement device, called the NOKOV motion capture system \[47], was employed to measure displacement field of the physical model. The system includes infrared optical cameras Mars9H \[45], motion capture software, a Cal-R-SET device, reflective markers, and a POE switch. After assembling the system, the number and positions of the cameras were determined based on the available space and model size. The Cal-R-SET device then calibrated the arrangement and established a spatial coordinate system to capture responses within the measurement range. Reflective markers were attached to the test model as tracking points, and the vibration response was recorded by calculating the displacement of the marker's center from images captured by the multiple cameras. The NOKOV motion capture system utilizes a three-dimensional optical measuring technique that achieves submillimeter accuracy, having been rigorously validated in previous studies \[48].

Citation Wu C, He S, Yuan B, et al. An improved NExT-DMD for efficient automated operational modal analysis[J]. Applied Mathematical Modelling, 2026: 116823.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001690292900001

DEOA-SLAM: Real-time object-aided SLAM for dynamic indoor environments with resource-constrained devices

Keywords

Visual SLAM; Object-aided SLAM; Dynamic environments; Semantic map; Resource-constrained devices

Abstract

This article presents DEOA-SLAM, a real-time object-aided visual Simultaneous Localization and Mapping (SLAM) system that enables efficient localization and semantic mapping in dynamic indoor environments on resource-constrained platforms such as mobile robots. The system integrates the YOLOv5 model into the ORB-SLAM2 framework to detect both dynamic and static objects. By combining depth information, semantic masks of dynamic objects can be efficiently generated to remove dynamic feature points prior to camera tracking. The static objects are tracked and reconstructed as ellipsoids, and these ellipsoid models are continuously optimized during tracking. Then, an object-aided relocalization algorithm is incorporated for pose recovery when feature-based relocalization fails. The resulting lightweight semantic map includes both sparse feature points and static objects represented by ellipsoids, where dynamic feature points are removed. Extensive experiments have been performed on dynamic sequences of the TUM RGB-D dataset to demonstrate the effectiveness of the proposed system in terms of localization accuracy, real-time performance, and semantic map quality. In addition, a conference room dataset has been built to evaluate the SLAM and relocalization performance of DEOA-SLAM in real world. Benefited from the dynamic object removal, static object reconstruction and tracking, DEOA-SLAM provides a real-time and robust means to object-aided semantic SLAM in dynamic indoor environments with resource-constrained devices.

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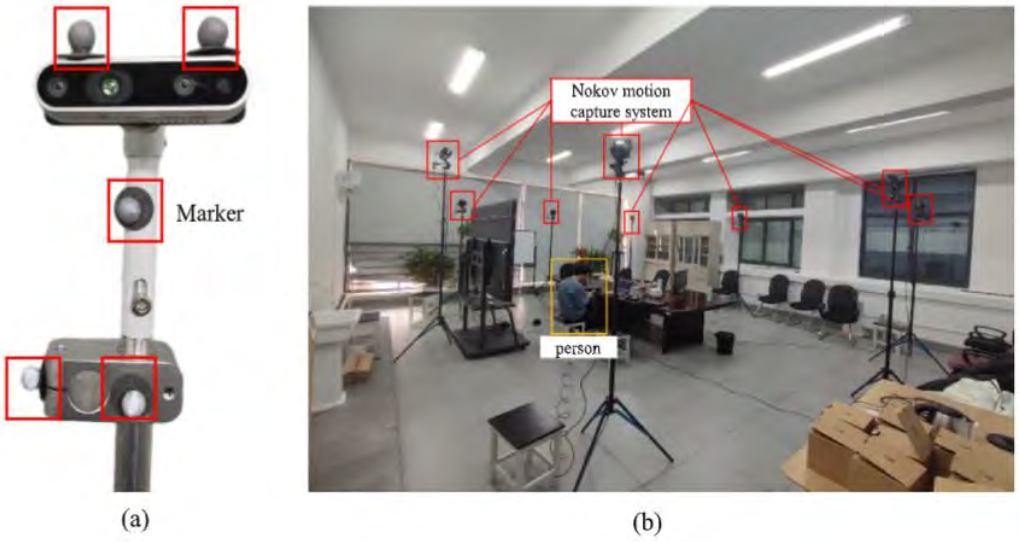

Fig. 11. Data collection equipment and conference room scene.

How NOKOV Contributes to the Research

A RealSense D435 camera was used to acquire RGB-D images of the scene. As shown in Fig. 11a, five reflective markers were attached to the camera to measure the ground truth of camera poses using a Nokov motion capture system with eight Mars2H cameras. Five different sequences have been created. As described in Table 6, the person moved at different speeds in four of the sequences. In the fifth sequence, the walking speed is similar to the mid sequence, the camera experiences large rotations toward the ceiling and then resumes its normal orientation four times during movement, to evaluate the object-based relocalization of DEOA-SLAM.

Citation Han D, Li Y, Chen S. DEOA-SLAM: Real-time object-aided SLAM for dynamic indoor environments with resource-constrained devices[J]. Displays, 2026: 103466.

Link https://www.sciencedirect.com/science/article/pii/S0141938226001290

Cyber-Physical Explorations of Collective Robotic Construction using Agent-Based Modelling

Keywords

Collective Robotic Construction(CRC) · Agent-based Modelling and Simulation (ABMS) · Behavioral Fabrication · Swarm robotics · Construction Automation

Abstract

Collective robotic construction (CRC) is an emerging subset of on-site construction robotics, which, despite its interdisciplinary nature, remains predominantly centered within the field of engineering. The goal of this research is to create a highly accessible workflow for developing and working with CRC systems that allows for their cyber-physical control. To demonstrate this concept, a low complexity robotic system was created in conjunction with an agent-based model (ABM) and associated software framework, enabling direct design and control of a swarm of mobile robots. The proposed system consists of a team of homogenous mobile robots that can actively rearrange a set of identical custom digital materials. The developed robotic system was conceptually extended, and the provided workflow was experimentally tested in a workshop setting with architectural students. The results of the workshop, which included four different conceptualizations of the provided robotic system, investigated various research topics within CRC, demonstrating the ability of architects to aid further conceptualization of research in the field.

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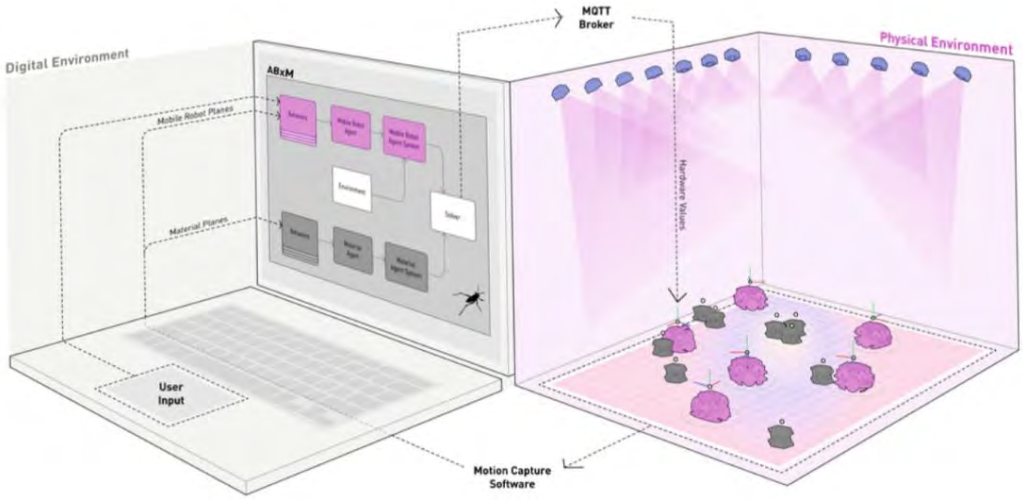

Fig. 4. Cyber-physical workflow diagram

How NOKOV Contributes to the Research

On the top of both the mobile robot and the digital material are unique patterns of retroreflective spherical makers, which allow them to be tracked using an external vision system. This is important for the eventual control of the system using the developed cyber-physical workflow. The entire robotic system is, thus, composed of mobile robots, digital material and an external motion capture system. Camera setups from NOKOV and OptiTrack were both tested.

Citation Leder S, Siriwardena L, Kragl P, et al. Cyber-Physical Explorations of Collective Robotic Construction using Agent-Based Modelling[C]//Robotic Fabrication in Architecture, Art And Design Conference. Springer, Cham, 2026: 3-18.

Link https://link.springer.com/chapter/10.1007/978-3-032-22607-5_1

Research on the Design and Experiment for Obstacle-Crossing Capability of a Wheeled-Claw Deformable Mobile Platform With Large Expansion Ratio

Keywords

cross-slope traversal; deformable wheel-claw; large expansion ratio; lateral slope driving; obstacle-crossing performance; radial expansion mechanism

Abstract

To enhance adaptability and obstacle-crossing performance in unstructured environments, this study proposes a large-expansion-ratio deformable mobile platform, referred to as the \"Wheel-Claw Climber,\" which is based on spatial folding and linkage deformation mechanisms. The platform incorporates a radially expandable deformable wheel with a maximum expansion ratio of 2.72, substantially exceeding the existing benchmark of 2.4. The \"Wheel-Claw Climber\" operates in three distinct configurations-wheel, claw, and intermediate-enabling adaptation to diverse terrains. An obstacle-crossing model is established, and the maximum obstacle-crossing height is determined to be 4.5R, representing a 27.7% improvement over current designs and demonstrating superior obstacle-surmounting capability. Furthermore, a cross-slope traversal strategy is proposed, whereby deformation and expansion of the low-side wheel relative to the high-side wheel increase passability and stability by 31.1% and 21.65%, respectively, on the same slope. Experimental validation confirms that the Wheel-Claw Climber can seamlessly transition between wheel and claw modes. At a wheel rotation speed of 1 rad/s, the platform achieves a maximum obstacle-crossing height of 550 mm, with a 100% success rate for obstacles below 450 mm. Overall, the deformable wheel architecture and experimental findings provide new insights for the design and development of next-generation mobile platforms.

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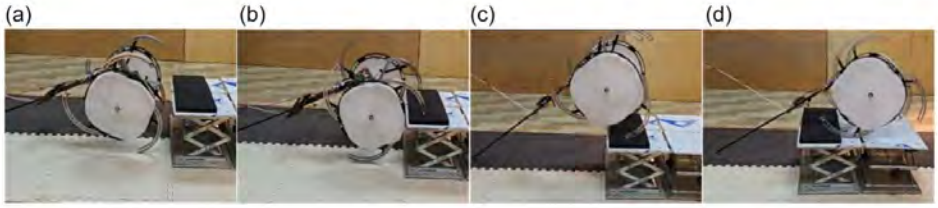

FIGURE 21 | The step obstacle-crossing process of the deformable wheel. (a) Approaching the obstacle. (b) Beginning to cross the obstacle. (c) Climbing onto the step. (d) Completing the obstacle crossing. [Color figure can be viewed at wileyonlinelibrary.com]

How NOKOV Contributes to the Research

Figure 20 presents the experiments of the wheel–claw mobile platform operating on a flat surface in both the circular wheel mode and the wheel–claw mode. Figure 21 illustrates the obstacle-crossing process of the deformable wheel. The entire motion process was analyzed by capturing and recording the position of the wheel center using the Nokov motion capture system, and the corresponding results are shown in Figure 22.

Citation Meng Q, Ke Z, Wei W, et al. Research on the Design and Experiment for Obstacle-Crossing Capability of a Wheeled-Claw Deformable Mobile Platform With Large Expansion Ratio[J]. Journal of Field Robotics, 2026.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001798019800001

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Dynamics and geometric optimal control of a planar air-bearing spacecraft simulator

Keywords

Lie Group; Spacecraft simulator; Geometric control; Air-bearing experiments

Abstract

One of the most popular micro-gravity ground test of space missions is planar air-bearing spacecraft simulator equipped with controllers to perform both pose stabilization and trajectory tracking in a simulated space mission. Previous studies based on the double-integrator equations neglect the geometric structures of the dynamics of the simulator. To address this problem, this paper begins with the continuous dynamic equations formulated on both left and right trivializations of Lie group SE(2), and then presents the intrinsic proportional-derivative controllers derived from these equations. Based on the discrete variational principle, this study presents a Lie group variational integrator derived for the time integration of the dynamic equations of the simulator. Then, the discrete geometric optimal controller is established by including the Lie group variational integrator as equality constraint equations into the optimal control problem. This work also prepares the proposed controllers in simulations in terms of accuracy, convergence rate, and control cost. Numerical results show intrinsic geometric characteristics of the pose trajectories obtained by using different controllers. To further investigate the real-time performances of different controllers, the paper presents a prototype of the planar air-bearing simulator and the experimental tests of pose stabilization and circle tracking. The experimental results are in good agreement with the numerical ones obtained from simulations.

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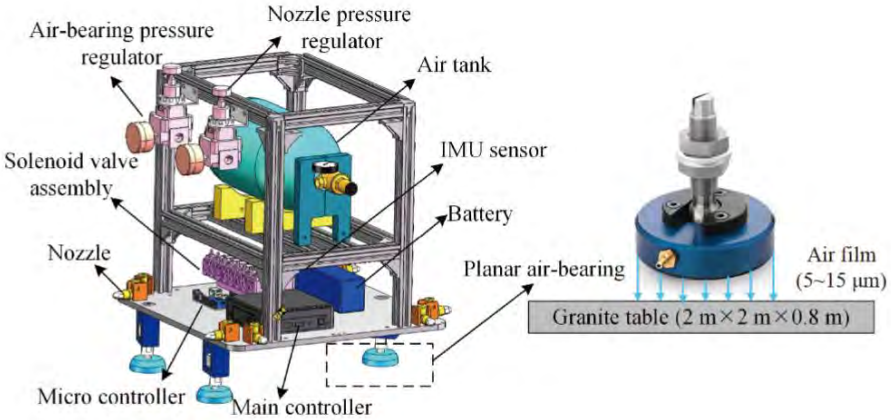

Figure 9 Composition of the designed planar air-bearing simulator.

How NOKOV Contributes to the Research

Table 3 shows the brands and specifications of the key components of the simulator prototype. The main controller is an on-board computer with the operating system of Ubuntu 16.04 LTS, CPU of Intel(R) Core i5-8259U @2.3 GHz and memory of 8 GB. The main controller collects and filters the pose and velocity measurements from sensors of the inertial measurement unit (IMU) and motion capture cameras.

Citation Wang S, Chen J, Song X, et al. Dynamics and geometric optimal control of a planar air-bearing spacecraft simulator[J]. Acta Mechanica Sinica, 2026, 42(3): 524797.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001688458900001

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BiLSTM-Chan 算法在超宽带室内定位中的应用

关键词

室内定位;超宽带；双向长短期记忆神经网络；注意力机制；深度学习

摘要

针对 UWB 在室内定位中因人员走动引起的非视距误差(NLOS)，以及常规神经网络训练后基站不能移动的问题，本文提出了一种基于融合双向长短期记忆神经网络的 Chan 算法(BiLSTM-Chan)。该算法首先通过双向长短期记忆神经网络处理 UWB 时序数据，给出超宽带(UWB)时序数据的误差修正值，然后依靠 Chan 算法计算得到最终三维坐标。双向长短期记忆神经网络能够综合过去与未来的信息，更好地捕捉到时序数据中的特征信息。在网络中加入注意力机制能够帮助网络分析 BiLSTM 层提取的关键特征，让神经网络的预测更加准确。本文通过仿真试验和实测试验，对 BiLSTM 算法、Chan 算法和最小二乘(LS)算法进行了对比。结果表明，相比于 BiLSTM、Chan 和 LS 算法，BiLSTM-Chan 算法的精度分别提高了 30. 66%、61. 78%和 61. 96%。

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图 6　试验真实场地

NOKOV 度量动作捕捉在研究中的应用摘录

为了验证本文算法在现实生活中的可行性，进行了实地试验，试验场地位于河南理工大学测绘学院。在 NOKOV 三维动作捕捉系统环境下，使 用 Decawave 公司的 DWM1000 定 位 模 块，采用双边测距算法(double-sidedtwo-wayranging，DS-TW R)得到距离信息，减小超宽带在测距中由时钟偏移引起的测距误差［17］。开展测距试验，验证定位算法在实际应用中的可行性，并比较不同算法下 UWB 系 统 的定位精度。NOKOV 动捕系统的定位精度达亚毫米级别，其定位结果可作为衡量 UWB 系统定位精度的参考值。为了模拟 UWB 数据中的 NLOS 误差，试验场地内会有人员来回走动。如图 6 所示。

引用格式 赵辰瑞,连增增,田亚林,等.BiLSTM-Chan 算法在超宽带室内定位中的应用[J].测绘通报,2025,(05):100-105.DOI:10.13474/j.cnki.11-2246.2025.0517.

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低成本惯性传感器的信号增强与手势识别

关键词

惯性传感器；手势识别；复杂网络；信号增强；确定性；随机误差

摘要

针对低成本惯性传感器中普遍存在的严重随机误差，提出了一种三阶段信号增强策略，通过复杂网络确定性指标，首次实现了对 IMU 信号随机性的量化，进而利用经验模态分解、小波变换对随机误差进行有效控制。进一步，首次在 IMU 运动识别任务中将时频特征与复杂网络拓扑特征相结合，在不同用户运动习惯各异和 IMU 型号多样且成本低廉的情况下，将 62 种三维手势动作的识别精度提升至 92.4%。此外，对比了多种机器学习与深度学习模型在手势识别任务上的精度，进一步论证了复杂网络拓扑特征在运动状态识别、时间序列分析领域的重要价值。

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图 4　借助光学传感器对惯性传感器进行标注

NOKOV 度量动作捕捉在研究中的应用摘录

用 Nokov 光学运动捕捉系统与惯性传感器同步采集运动数据，进而为后续机器模型的训练、测试提供所需标签，实验场景如图 4 所示。最终，本文将 9300 组数据随机划分 8500 组数据作为训练集，800 组数据作为测试集。

引用格式　杨森乔,王一峰,赵毅.低成本惯性传感器的信号增强与手势识别[J].传感技术学报,2023,36(08):1201-1209.

链接
https://kns.cnki.net/kcms2/article/abstract?v=lxIxReJOxldAcFCcM9e2yBTSwkyHk23ZYewjv-EiBp5evxJApHsGQK0JWJ8mr-H24T_WaEaZ4UtCuSMuH3B5LOXc2mkM1Cb-eGPHU4owEv_P9MUkRn5lZg==&uniplatform=NZKPT&language=gb

动态模态分解的结构模态参数自动辨识

关键词

模态参数辨识；动态模态分解(DMD)；聚类算法；自动化辨识；数据驱动

摘要

结构模态参数的自动化辨识是当前结构动力学领域的研究热点，然而传统的时域辨识方法在大量响应数据下存在效率 低的问题。结合动态模态分解(dynamic mode decomposition, DMD)技术和密度聚类(density-based spatial clustering of applications with noise，DBSCAN)算法，利用结构自由衰减响应，提出了一种快速结构模态参数自动辨识方法。根据真实模态 参数在 DMD 技术中的秩稳定性，提出了结构模态的自动辨识策略，即通过判断轮廓系数(Sil)和候选真实模态簇数量反映聚 类得到簇的模态成分，利用其变化特点自动地确定 DBSCAN 的关键超参数，实现准确地辨识结构模态参数。以简支梁模型为 例，与有限元方法(finite element method, FEM)结果对比，说明了模态参数自动辨识的准确性。以非均质悬臂板模型为例，与 特征系统实现算法(eigen realization algorithm, ERA)对比，本文方法避免了 Hankel 矩阵选择问题，展示了在大量数据条件下快 速辨识结构模态参数的能力。以机翼实物模型为例，通过非接触式的动作捕捉系统采集结构位移响应进行模态参数自动辨 识，与 LMS. Test Lab 模态测试系统结果对比，验证在实际场景中应用的有效性；并通过该机翼的实物模型和有限元模型分析 了抗噪性，结果表明在 10%的噪声干扰下能够准确地辨识出结构模态参数。

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图 15 实验现场布置及红外光学相机分布

NOKOV 度量动作捕捉在研究中的应用摘录

为减小附加位移传感器的影响，本文采用了非接触式三维红外光学技术——NOKOV 度量光学三维动作捕捉设备采集位移响应。其具有亚毫米级的精度\[19]，且仅需要在模型上布置轻质的反光小球即可采集该点三维位移响应，很好地解决了传统传感器布置问题。

引用格式 吴承远,贺顺,张英琦,等.动态模态分解的结构模态参数自动辨识[J/OL].振动工程学报,1-12[2025-09-16].https://link.cnki.net/urlid/32.1349.TB.20250415.1334.002.

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多指灵巧手拟人操作规划方法研究

关键词

多指灵巧手；操作目标物体；指态规划；操作运动仿真；

摘要

多指灵巧手作为机器人的末端执行器,是机器人的重要组成部分,具有高度的灵巧性和操作性,一直是机器人领域的研究热点之一。目前对多指灵巧手的研究大多集中在灵巧手结构的开发和抓取运动的规划,对于抓取之后的精细操作运动和重定位分析等方面的研究尚未完全展开。建立一定的操作运动规划可以实现多指灵巧手像人手一样灵巧的操作不同形状的物体,因此,研究手指精细操作的指态过程和运动模型对多指灵巧手的开发和灵活性运用具有重要意义。

本课题针对多指灵巧手的操作运动规划问题进行了分析与研究,设计了手指操作的运动指态,建立了手指操作运动学模型,并通过基于 Open GL 自主研发的仿真模拟平台仿真和实验验证了理论模型的正确性。本文主要的研究内容如下:

（1）研究了人手抓取操作目标物体过程的规律和操作策略。人手作为灵巧多指手的灵感来源,可以完成很多复杂的操作运动,分析人手操作过程习惯模式和存在的规律性,提出了适合机械手操作的运动指态,推导出符合的理论模型。对具体工作任务进行降维分析,细化为许多子任务,将整体运动过程"积木化",拆分成多个动作模块,作为操作不同目标物体时的运动基础。

（2）建立多指灵巧手操作物体的数学模型。分析灵巧手本身的结构特点,研究多指灵巧手操作物体时手指指尖与手指关节角位置之间的关系,包括正、逆运动学模型和手指可达空间,为后续的操作规划研究提供理论依据。对多指灵巧和目标物体的操作建模作了简化和抽象,将人手的操作习惯和指态融入多指灵巧手模型中,针对不同外形的目标物体设计指尖运动轨迹,建立理论模型。

（3）讨论了手指的操作性指标,生成不同指态模式下的算法。考虑到指尖完全脱离物体表面做操作运动的前提条件,基于评价指标以及物体和关节的速度映射关系,针对于不同的起始指态,生成了两种不同指态模式下的算法。

（4）用自主研发的仿真平台对手指建模并对运动过程进行了仿真分析。实验结果和理论分析基本吻合,验证了三指操作目标物体运动模型的有效性和准确性。上述研究的结果表明,本文建立的操作指态和基本理论模型能够比较准确地描述简单目标的手内精细操作过程,本文的研究成果为多指灵巧手的进一步开发和精细操作复杂物体提供了初步的理论基础。

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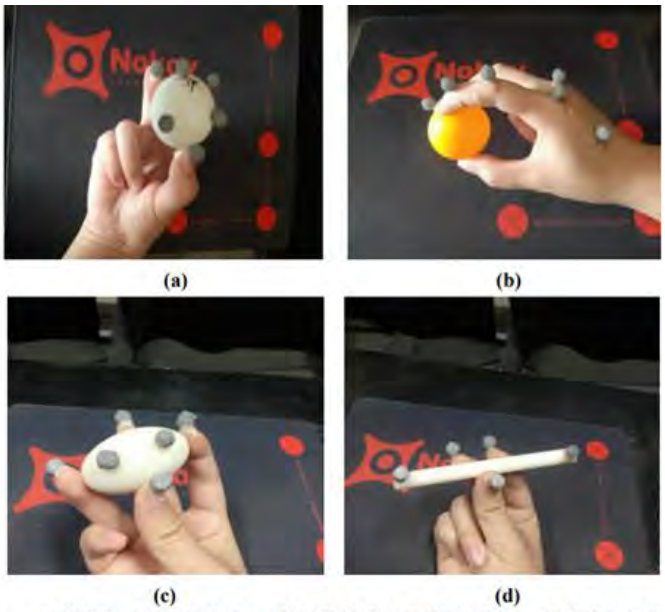

图 2-5 三指操作目标物体实验 (a)转球体指尖运动轨迹实验 (b)转球体食指关节角度测量实验 (c)转椭圆体指尖运动轨迹实验 (d)转杆体指尖运动轨迹实验

Figure 2-5. Three-finger operation on target object (a) Experiment of the motion trajectory of a rotating sphere fingertip (b) Measurement of angle of index finger joint (c) Experiment on the trajectory of spheroidal fingertips (d) Experiment of fingertip movement trajectory

NOKOV 度量动作捕捉在研究中的应用摘录

本章根据人手外科解剖学的手指构造和已有的人手运动学模型，分析手指各指骨长度和手指间相对位置关系与运动规律，在前人研究的基础上设定手指操作目标物体的指态规划并通过 NOKOV 光学三维动作捕捉系统对手操作实物的运动进行捕捉。将视觉识别到的人手数据进行处理分析，从实验数据中分析手指和关节间可能存在的运动关系，总结出人手操作可能存在的规律，以应用于后续第三章和第四章中多指灵巧手精细操作物体的手内操作指态规划模式和数学模型的研究。

模拟用人手按照所规划的指态操作乒乓球、椭圆体和长杆，对这一过程用 NOKOV 光学三维动作捕捉系统的摄像功能对手指操作目标物体的过程进行摄像。 NOKOV 系统可采集人手的操作过程的运动轨迹和运动学参数，并进行数据处理。

用于实验的 NOKOV 光学三维动作捕捉系统装置如图 2-5 所示，待操作的椭圆体和杆体是专为实验定制，通过合理设计物体内部的结构，对其做了中空处理， 使目标物体的重量尽可能减小，这里采用 3D 打印的方法制造。由于实验条件所致， 反光球具有体积，且它的位置并非刚好仅位于指尖与物体的接触点上，在实验结果分析时会对其进行相应的处理，尽可能保证实验的真实性和可靠性。

引用格式 张亚琪.多指灵巧手拟人作规划方法研究[D].浙江工业大学，2020.DOI：10.27463/d.cnki.gzgyu.2020.001264.

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复杂光照环境下空间目标相对位姿测量方法研究

关键词

相对位姿；MSRCP；椭圆检测；双目视觉；在轨服务

摘要

为解决空间复杂光照环境下可见光相机获取的图像照度不一、信息失真、特征不完整导致的目标航天器相对位姿求解困难的问题，提出了一种基于图像增强和弧段特征的双目视觉相对位姿测量方法。首先通过基于带色彩保留的多尺度 Retinex（Multi-scale Retinex with Chromaticity Preservation， MSRCP）自适应图像预处理方法提升空间暗弱光、局部强曝光环境下的图像质量；然后利用基于边缘弧支撑线段的椭圆检测算法提取目标航天器表面星箭对接环的弧段特征，并拟合得到椭圆轮廓；最后利用双目相机搭建了空间相对位姿测量物理仿真实验平台，建立双目空间椭圆锥测量模型解算目标的六自由度相对位姿，实现了近距离正常光照和暗弱光照场景下目标航天器相对位姿求解。实验结果显示：在正常光照场景下，相对位置平均误差不超过±20mm，相对姿态平均误差不超过±0.3°；在暗弱光照场景下，相对位置平均误差不超过±30mm，相对姿态平均误差不超过±1°。研究成果为近距离空间交会对接等在轨服务任务中的目标识别与测量提供了参考，具有技术借鉴价值。

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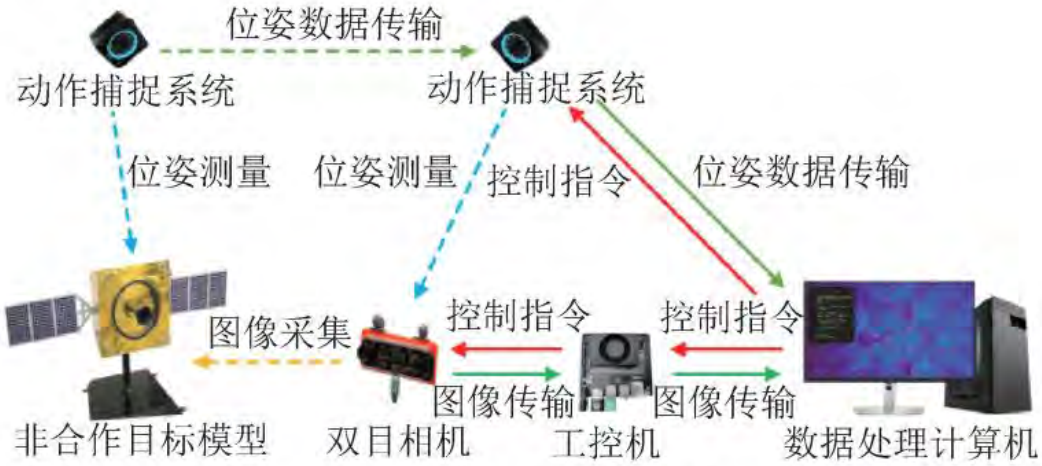

图 8　实验系统组成图

Fig.8　Diagram of experimental system composition

NOKOV 度量动作捕捉在研究中的应用摘录

采用 NOKOV（度量）MARS 系列 1200 万像素动作捕捉相机进行测量，频率为 300Hz，3D 测量精度在 mm 级。动作捕捉系统测量精度极高，实际实验中以动作捕捉系统测量得到的位姿信息作为真值，双目相机测量得到的位姿作为测量值，从而求解测量误差。

引用格式　丁奕冰,王海明,苏振华等.复杂光照环境下空间目标相对位姿测量方法研究[J].计测技术,2024,44(02):56-69.

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https://kns.cnki.net/kcms2/article/abstract?v=Uq4Diyda8XCPRF0TnCNLcPqNILeXZRUPv1pyxBdfR7PQQXZ3dUbwoREKkaVLrEbNSX4zW4xE2_mjhKndpxx5GrIDEEO_rYvBtLxKjX-rrcZPREUqbrRDmPVzw5STg1A_&uniplatform=NZKPT&language=gb

机器人非质点模型快速轨迹优化

关键词

移动机器人；非质点模型轨迹规划；轨迹优化；碰撞检测；

摘要

移动机器人不仅为人们的生活提供了便利,同时也极大地提高了生产的效率,被广泛地应用于社会的方方面面。轨迹优化作为移动机器人运动规划领域中的关键技术,是备受国内外研究人员关注的热点课题。轨迹优化的目的是将初始参考轨迹优化成一条满足各项约束条件的机器人可执行轨迹。在许多简单任务中,将移动机器人建模为一个质点能够进行高效的碰撞检测。然而,为了使机器人能够在复杂环境中灵活穿行,越来越多的工作致力于机器人非质点模型的轨迹优化方法研究。它要求在进行碰撞检测时考虑机器人整体形状与环境的碰撞,这引入了更为复杂的计算,使得优化难以在有限的板载计算资源中进行。目前,一些现有的工作使用基于安全走廊的轨迹优化方法,它们将环境中的可通行区域建立为一系列凸包的集合,但这种方法需要走廊的交界处能够覆盖整个机器人的形状,这一严格的要求在狭窄环境中难以实现。也有方法将机器人和环境分别建立为凸多边形,通过判断凸多边形间的距离来构建安全性约束,然而这种方法难以应用于非凸形状机器人的轨迹优化。也有方法使用欧式符号距离场来描述机器人到最近障碍物的距离,虽然欧式符号距离场能够充分描述可通行区域,但权衡计算效率和场的范围并非易事。针对上述问题,本文主要设计了一种机器人非质点模型快速轨迹优化算法,包括快速碰撞检测算法和机器人位置姿态联合优化算法。具体来说,本文的研究内容和创新点为:(1)机器人非质点模型快速碰撞检测。本文提出一种基于机器人自身形状建立的欧式符号距离场(简称 RC-ESDF),它预先建立在机器人的机体系,不需要根据传感器获得的环境信息进行实时更新；它天然能够应用于任意形状的机器人,甚至是非凸形状的机器人。在进行碰撞检测时,本方法忽略了未与机器人产生碰撞的障碍物信息,这大大降低了计算资源的消耗。(2)机器人位置姿态联合优化器。为了使机器人能够以合适的位置和姿态避开障碍物,本文基于 RC-ESDF 提出了一种联合轨迹优化器,对机器人的位置和姿态同时进行优化。文中对具有完整性约束和非完整性约束的机器人的各优化项进行了推导,说明该优化器适用于具有不同运动学约束的机器人。(3)实验验证。为了验证所提方法具有泛化性和鲁棒性,本文进行了大量的仿真实验与实物实验。仿真实验验证了本方法能够应用于不同形状的机器人,并且通过与其他机器人非质点模型轨迹优化方法进行对比体现了本方法的优势。本文对实物实验所需的机器人自主导航系统进行集成,融入了所提算法,通过结果说明本方法能够应用于实物机器人上,并在真实的障碍物密集场景中进行高效的轨迹优化。

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NOKOV 度量动作捕捉在研究中的应用摘录

在麦克纳姆轮机器人实验平台上，机载的环境感知传感器使用 Ouster64 线激光雷达，机器人姿态使用 RoboMaster A 型板自带的 IMU 获取，机器人实时定位的真值根据 NOKOV 动作捕捉系统融合 IMU 信息得到。所有的算法计算均基于 i5-1135G7 CPU 的 NUC 机载电脑实现，其操作系统为 Ubuntu 20.04。

引用格式 耿爽.机器人非质点模型快速轨迹优化[D].浙江大学，2023.DOI：10.27461/d.cnki.gzjdx.2023.000124.

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基于 SINS/WSN 的掘进机定位定姿研究

关键词

SINS；WSN；UWB；组合定位；掘进机

摘要

我国煤矿巷道和隧道掘进规模巨大，而掘进机作为巷道和隧道机械化掘进的重要设备，目前主要由人工操作，存在着安全性低、巷道成型质量差、工作效率低等一系列问题，掘进机自动化和无人化需求越来越迫切，而掘进机定位定姿技术作为掘进机自动化和无人化的基础，亟需进行研究。本文在基于里程计辅助 SINS 定位和基于 EKF 滤波的 UWB 定位的基础上，将两种定位方式进行数据融合，从而提高定位系统的定位精度。

（1）针对纯捷联惯导系统中的累积误差问题，基于惯性导航工作原理，建立了坐标系之间的转换关系，在捷联惯导系统位姿解算策略基础上，引入里程计辅助解算，基于捷联惯导系统和里程计误差模型，建立里程计辅助捷联惯导系统组合定位模型。SINS 定位定姿仿真与实验结果表明，里程计辅助条件下，捷联惯导系统的累积误差在 x 和 y 方向上得到有效抑制，x 和 y 方向上的平均定位误差为 13.08cm 和 21.77cm，但在 z 方向上，仍然存在累积误差。

（2）综合分析各种 WSN 定位技术，选择 UWB 定位技术作为本文的研究对象。针对 UWB 定位过行程中存在的定位跳动问题，在 TOF 测距基础上，建立 UWB 定位解算模型，并对 UWB 定位的误差进行分析，基于 KF、EKF 建立 UWB 定位目标跟踪模型。从静态和动态定位两个方面进行了 UWB 定位实验，验证 KF 和 EKF 的滤波性能，经滤波处理后，UWB 的定位精度得到有效提高，EKF 滤波的定位精度最高，x 方向上平均误差为 15.33cm，y 方向上平均误差为 11.76cm，z 方向平均定位误差为 20.03cm。

（3）在里程计辅助捷联惯导和基于扩展卡尔曼滤波的 UWB 定位基础之上，建立 SINS/UWB 定位数据融合数学模型，采用松组合和紧组合对两种定位方式进行数据融合。在模拟巷道中进行了松组合以及紧组合定位实验，实验结果表明，松组合以及紧组合都能在一定程度上提高定位精度，紧组合的定位效果最好，能够较好的贴合实际的定位轨迹，紧组合 x 方向上平均定位误差为 12.08cm，y 方向上的平均定位误差为 6.03cm，z 方向上平均定位误差为 12.64cm。

（4）基于悬臂式掘进机试验台进行掘进机定位定姿实验，验证了基于里程计辅助 SINS 定位和基于 EKF 滤波的 UWB 定位的有效性和可靠性，掘进机试验台紧组合定位实验表明，在里程计辅助 SINS 和基于扩展卡尔曼滤波的 UWB 定位的基础上，组合后的定位结果相较于单一的定位方式，定位精度得到有效提高，x 方向上的平均定位误差为 8.65cm，y 方向上的平均定位误差为 11.34cm，z 方向上的平均定位误差为 11.04cm。

该论文有图 92 幅，表 17 个，引用格式 96 篇。

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图 5-7 NOKOV 动捕系统红外镜头及红外标识点

Figure 5-7 NOKOV motion capture system infrared lens and Infrared marking point

NOKOV 度量动作捕捉在研究中的应用摘录

本文采用高精度 NOKOV 动作捕捉系统，该系统采用多个高分辨率红外镜头，镜头及红外标识点如图 5-7 所示，动捕镜头参数如表 5-5 所示，在对整个系统进行标定后，将红外标志点安装在目标机体上，在采集区域内，只要能同时被两个镜头拍到，就可以确定该点的位置，当镜头以足够高的速度连续拍摄时，就可以获得移动目标的高精度移动轨迹，定位精度可以达到毫米级。动捕系统工作流程如图 5-8 所示，首先布置红外相机覆盖试验区域，使用上位机软件完成相机相关参数的设置，然后利用带有红外标识点的 T 形杆进行相机标定，在运载体上安装红外标识点，运载体移动过程中，红外镜头按设定频率不间断拍摄，最后通过网线将所有的红外拍摄信息汇总到 POE 交换机上，POE 交换机通过网口连接到电脑上位机，再由上位机软件对四个红外镜头拍摄的数据信息进行结算分析，得到红外标识点的移动轨迹。

引用格式 姚健．基于 SINS/WSN 的掘进机定位定姿研究[D].中国矿业大学，2021.DOI：10.27623/d.cnki.gzkyu.2021.001138.

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基于 TOA 的迭代最小二乘定位算法研究

关键词

迭代加权；加权最小二乘；超宽带系统；TOA 测距

摘要

室内环境中基站与标签之间的距离会受到随机误差的影响,针对超宽带(UWB)系统的定位特性,提出了一种迭代加权最小二乘(IRLS)算法削弱测距随机误差的影响.首先,利用加权最小二乘算法获得标签的三维坐标.其次,通过构建中间变量,利用中间变量与位置坐标的关系构造迭代关系,并通过迭代计算提高标签三维坐标点位精度,得出最优解.仿真结果表明,在静态定位实验中,IRLS 算法与经典最小二乘(LS)算法的平均点位误差分别为 11.96 cm 和 13.42 cm,IRLS 算法的定位结果优于 LS 算法;在动态定位实验中,经过卡尔曼滤波算法平滑处理后,IRLS 算法的点位精度相比经典 LS 算法提升了 12.82%.因此,IRLS 算法可以显著提高 UMB 定位系统的点位精度。

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图 3　实验场地示意图

Fig. 3　Experimental site schematic diagram

NOKOV 度量动作捕捉在研究中的应用摘录

采用 NOKOV 三维动作捕捉系统采集标签的坐标信息,该系统的定位精度可达亚毫米级别,其定位结果可以作为衡量 UWB 系统定位精度的参考值。

引用格式　陈浩,连增增,董佳琪等.基于 TOA 的迭代最小二乘定位算法研究[J].导航定位与授时,2024,11(05):17-24.DOI:10.19306/j.cnki.2095-8110.2024.05.002.

链接

https://d.wanfangdata.com.cn/periodical/dhdwyss202405003

基于 T 时间间隔的可移动相机网络的动态覆盖

关键词

T 时间间隔；动态覆盖；视觉巡检；相机网络

摘要

相机网络的覆盖问题是学术研究中的热门课题，视觉巡检作为覆盖问题的应用之一，在工业生产和日常生活中发挥了重要作用。从相机网络在任务过程中是否运动的角度来看，覆盖问题可以分为静态覆盖和动态覆盖。静态覆盖问题的研究目的是通过优化相机网络固定的位置和姿态来提高覆盖性能，而视觉巡检任务要求相机连续运动，静态覆盖无法满足要求。因此，本文针对相机网络的动态覆盖问题进行了研究。

由于相机在实际应用中具有各向异性，这对其覆盖效果具有不可忽视的影响，因此本文构建的覆盖模型是三维视锥体在二维平面上的投影，保留了此特性。为了评价相机所捕获信息的覆盖质量，本文引入同胚变换的概念，通过计算同胚距离，定义了覆盖强度。此外，本文考虑了覆盖的可持续性，提出了 T 时间间隔的概念。具体来说，任务点在被覆盖到的 t 时刻起，被覆盖的状态持续 T 秒的时间，在 t+T 时刻后变为失效状态，等待下一次被相机覆盖。T 时间间隔的取值可以根据用户需求或任务要求来决定。

本文提出了基于 T 时间间隔的可移动相机网络的动态覆盖问题，主要的研究内容如下：

1.相机作为视觉巡检的重要工具，传统的二维模型不具有三维的真实性，本文将三维视场模型投影到二维平面上构建覆盖模型，使其可以直接用于三维中相机的覆盖任务。本文还对覆盖模型进行同胚变换以降低各向异性导致的计算复杂度，基于欧氏距离计算出同胚距离，从而设计覆盖强度作为评估标准。

2.本文设计了基于 T 时间间隔的动态覆盖代价函数，具有一般性，随着 T 的取值不同，可以解决不同的覆盖问题，并通过仿真进行验证。

3.针对智能小车的硬件条件和结构限制，本文引入了具有非完整性约束的运动学模型，并且在使用梯度上升算法优化代价函数时考虑了该模型，实物实验的结果验证了控制率的有效性。

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图 5.22 NOKOV 动作捕捉平台

NOKOV 度量动作捕捉在研究中的应用摘录

本实验在 NOKOV 动作捕捉平台下进行，如图 5.22 所示。NOKOV 是一种先进的动作捕捉平台，具有高精度、高效性、灵活性、实时性、易用性和可扩展性等优点，适用于各种不同领域的运动分析和仿真应用。因此，智能体的位置、朝向信息不需要从机身的雷达和 IMU 读取，可以由该系统实时记录，精度更高。在实验中，通过图像匹配技术对相机模型参数的误差进行校正，减小误差对实验结果的影响。

引用格式 陈怡.基于 T 时间间隔的可移动相机网络的动态覆盖[D].武汉科技大学，2023.DOI：10.27380/d.cnki.gwkju.2023.000590.

链接

https://kns.cnki.net/kcms2/article/abstract?v=DFdco8SIy0IP4DTj0fF0XTgmHScc8F-NNiE65-ZXzr8xvpR9gbFJq6r9atxOqBZOCO2IYdDvu6RN4N7I7KeZxPhenxiSX7iJFFu6H9_NCrbpi-LkE-fv8A==&uniplatform=NZKPT&language=gb

基于多点动态捕捉的机器人关节位移与几何参数标定

关键词

串联机器人；动捕测量；关节位移辨识；几何参数标定

摘要

机器人关节位移及几何参数误差是导致位姿出现误差的主要原因，对二者进行高精度标定可提高机器人的绝对精度。传统标定方法的精度受机器人位姿的影响，且需多次实验。本文提出一种基于多点动态捕捉测量的标定方法，可通过单次实验，同时标定串联机器人的关节位移和几何参数。首先基于多点动捕测量获取机器人各连杆上靶标点的 3D 坐标，结合罗德里格斯变换实现关节位移的求解。其次结合机器人运动学模型和坐标转换关系，实现几何参数误差小量的标定。对方程线性化处理以提高计算效率，并用最小二乘法降低噪声对结果的影响。最后通过对 6 自由度串联机器人进行仿真，验证了该标定方法的可行性。

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NOKOV 度量动作捕捉在研究中的应用摘录

由于在动态捕捉中，相机的测量噪声应为高斯白噪声，因此在各 靶 标 点 随 时 间变化的三维坐标上，添加白噪声信号，模拟真实的测量结果。参考 NOKOV Mars 2H 相机的三维精度，使用标准差为 0.2 mm 的白噪声模拟相机动态测量误差。

引用格式 李婧瑜，杨简宁，张笑宇等.基于多点动态捕捉的机器人关节位移与几何参数标定[J].力学季刊，2022,43（01）：34-45.DOI：10.15959/j.cnki.0254-0053.2022.01.004.

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基于多目视觉的下肢运动识别研究

关键词

多目视觉；三维空间；下肢运动；膝关节屈伸；骑行相位

摘要

人体运动捕捉是运动科学、仿生机器人、康复医学等领域重要研究方向。视觉动作捕捉技术可在不接触人体的条件下捕获人体运动数据,自然交互体验感强,使用成本低。但在下肢运动捕捉中,该技术存在关节遮挡与自遮挡、三维信息还原存在歧义等问题。本文基于多目视觉技术捕捉人体下肢运动,利用 Open Pose 模型结合摄像头位姿信息准确解算下肢关节点在三维空间的运动数据,通过设计骑行相位识别实验证明运动数据的适用性和实用性。本文主要研究内容如下:1.针对视觉动作捕捉技术存在的问题,探讨多个摄像头采集运动数据的技术和设计,包括摄像头参数设置、单个摄像头畸变矫正、多个摄像头间位姿求解,以及用于衡量运动数据准确性的动作捕捉系统环境搭建。2.针对三维空间中下肢运动数据解算,选择 Open Pose 模型获取不同视角中下肢关节点二维图像像素坐标和置信度,结合摄像头位姿信息基于三角测量算法解算三维空间中下肢运动数据,包括关节点三维坐标、关节角度和关节点加速度。3.针对运动数据误差处理和准确性评估,设计膝关节屈伸运动数据采集实验。考虑原始数据保留情况,对比经五点三次平滑和基于残差分析的数字滤波处理后数据与原始数据的相关性,选取基于残差分析的数字滤波算法处理数据,以动作捕捉系统数据为标准,探讨从不同方位解算屈伸运动数据的情况及置信度间的关系。本文以骑行运动为例设计实验,通过支持向量机识别不同骑行速度时的骑行相位,结果表明,速度为 0.8m/s 测试集识别准确率为 90.49%,速度为 1.3m/s 时测试集识别准确率为 87.94%,速度为 2.1m/s 时测试集识别准确率为 83.90%。即通过多目视觉结合关节检测模型解算的三维数据可准确反映下肢运动变化情况。

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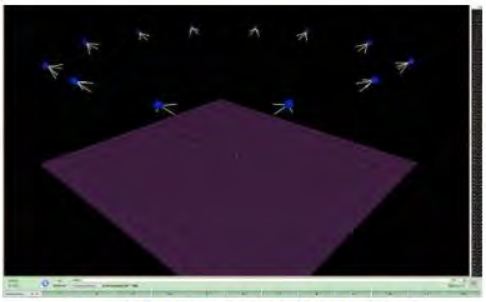
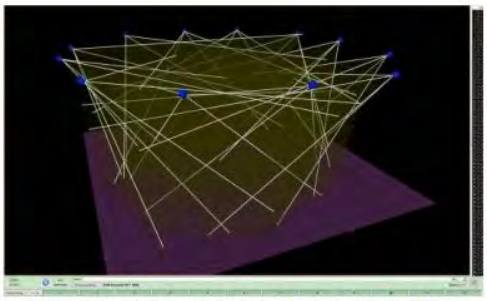
(a) 动作捕捉镜头布置



(b) 动作捕捉系统软件处理界面



(c) 动作捕捉系统镜头分布及视角范围

图 2.14 动作捕捉系统

NOKOV 度量动作捕捉在研究中的应用摘录

课题研究中实验结果以 NOKOV 动作捕捉系统采集的数据为标准进行验证。整 个动作捕捉系统包括 12 个 Mars 1.3H 型动作捕捉镜头，其分辨率为 1280×1024，数 据频率可调，最高可达 240Hz，数据采集延迟约为 4.2ms，视场角为 56.3°×43.7°，代 表可捕捉到的反光标记点的范围；一台 POE 交换机，用于数据传输；反光标记点若 干，贴于人体关节处记录人体运动轨迹；自开发的 seeker 数据处理软件，用于接收、 处理、显示反光标记点的运动轨迹。图 2.14(a)为实验室搭建的动作捕捉系统，图 2.14(b)为动作捕捉系统的处理软件。

引用格式 张钰佳.基于多目视觉的下肢运动识别研究[D].重庆邮电大学， 2022.DOI：10.27675/d.cnki.gcydx.2022.000123.

链接

https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C475KOm_zrgu4sq25HxUBNNTmIbFx6y0bOQ0cH_CuEtpsI97t9mOcvB6ycq18LTAKjo-jz9wyRq6oZECPfir29Ap&uniplatform=NZKPT

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基于改进高斯拟合的红外相机视角下标识点中心定位方法

关键词

光斑检测；图像分割；中心提取；光学测量；

摘要

针对红外相机视角下标识点中心提取问题，本文在分析其图像特征的基础上，提出一种粗细结合的分割及高斯拟合的方法以实现对标识点中心的定位。首先根据图像中标识点的灰度差异，对其进行 ROI 粗定位，去除背景反光对其分割的影响。随后对目标图像采用 K 均值聚类算法，实现目标分割。最后，通过剔除中心冗余信息的改进高斯拟合提取方法，得到标识点光斑中心坐标。实验结果表明，相较于灰度质心法、Hough 变换法和圆拟合法，本文方法对其中心提取稳定性误差均小于 0.1 像素，具有高重复性和稳定性精度。即使目标产生不同程度遮挡时仍具有较高精度，适合于红外相机视角下定位系统的标识点中心提取。

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图 12 实验设备

NOKOV 度量动作捕捉在研究中的应用摘录

实验选用 NOKOV MARS4H 型号红外相机，如图 12 所示，相机为红外镜头，通过向标识点处释放红外光，来实现对其捕捉。其相机分辨率为 2048 像素×2048 像素可达 410 万，采样频率为 180Hz。在视场的空间维度中对红外定位标识点进行图像采集，分别采用灰度质心法、Hough 变换法、圆拟合法和改进高斯拟合法来求解红外定位标识点目标的中心坐标。

引用格式 鲍勃屹，张辉，朱成顺等.基于改进高斯拟合的红外相机视角下标识点中心定位方法[J].激光杂志，2024,45（04）：59-64.DOI：10.14016/j.cnki.jgzz.2024.04.059.

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https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C45S0n9fL2suRadTyEVl2pW9UrhTDCdPD67O7bPVY80iqVUsbrEIMgrwzS4XHRJNHp92R3OzsggHQqIMhjOFZ5kJ&uniplatform=NZKPT

基于概率路图和蚁群优化的路径规划

关键词

路径规划；蚁群算法；概率路图；Bezier 曲线

摘要

路径规划是机器人和自主系统中的关键任务，其目标是在避开障碍物的同时从起点到终点位置找到最优路径。然而，路径规划是一个复杂的问题，在复杂的多障碍物环境中更具挑战性。本研究提出了一种结合概率路线图(PRM)和蚁群优化(ACO)算法的方法，以克服传统路径规划方法在寻找最优平滑路径方面的局限性。

提出的方法包括三个主要步骤。首先，构建一个概率路图来表示环境的配置空间。其次，利用蚁群算法基于信息素和启发式信息来寻找起点和目标点之间的最优路径。然后，在路径上添加控制点并利用 Bezier 曲线平滑路径。本研究的贡献有两个方面。首先，所提出的方法提高了路径规划过程的效率和准确性。其次，Bezier 曲线的使用减少了生成路径的转弯次数，增强了路径的平滑度。

实验结果验证了本文提出的方法在路径长度、平滑度和可行性方面的有效性。此外，该方法展示了对复杂环境的鲁棒性，使其适合实际应用。它可以扩展到各种机器人系统，包括自动驾驶汽车、无人机和移动机器人。

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NOKOV 度量动作捕捉在研究中的应用摘录

We used the NOKOV motion capture equipment to determine the platform's real position. Three reflecting identifying points were fixed to the platform and tracked by optical lenses positioned above the testing field. Because the NOKOV motion capture system's positioning accuracy approaches the sub-millimeter level, it gave reliable information for the trolley's real position and movement trajectory.

引用格式 Beavogui M. 基于概率路图和蚁群优化的路径规划[D].武汉科技大学，2023.DOI：10.27380/d.cnki.gwkju.2023.000584.

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基于广义刚度的多指手抓持稳定性分析

关键词

关节刚度；接触刚度；灵巧手；抓持稳定性；扰动力

摘要

近年来,仿人灵巧手成为热门的研究方向,大量学者对灵巧手抓持稳定性进行了研究。刚度是影响灵巧手抓持稳定的一个重要因素，本文基于旋量理论综合研究了灵巧手关节刚度和接触刚度与扰动力作用下的被抓持物体位姿变化的关系，在旋量空间中得出了广义刚度。并针对扰动力造成的软指与物体间的滚动情况，提出了一种等效接触切向刚度的方法。在广义刚度的基础上提出了扰动力椭球的概念，并以此定义了一种抓持稳定性指标。最后,设计了一个三指灵巧手对建立的理论模型进行了实验验证,证明了理论模型的有效性。

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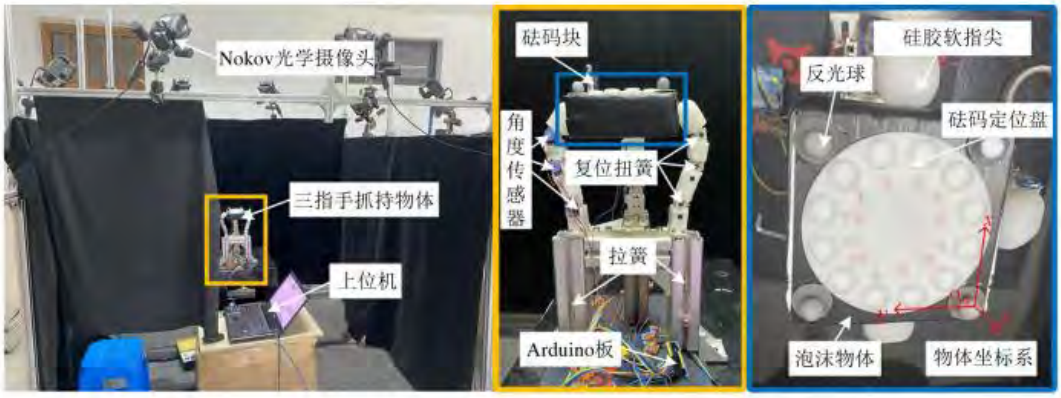

图 6　实验平台

NOKOV 度量动作捕捉在研究中的应用摘录

实验平台如图 6 所示，　实验采用了腱绳驱动的三指手对物体进行抓持。　为了保证实验过程中指尖与物体不发生滑动，　采用了黑胶带包裹的泡沫六面体作为被抓持物体，泡沫物体质量小，黑胶带能增大手指与物体之间的摩擦。　在腱绳中间加装拉簧模拟关节处的刚度，三指 手的位姿由关节处的角度传感器测得，物体的位姿由 Nokov 光学三维动作捕捉系统进行测量，整体的硬件 连接如图 7 所示。　该实验平台可以研究在某一刚度下、　不同大小方 向的扰动力对物体位姿的影响。

引用格式　谢贤铨，陈志培，陶志成等.基于广义刚度的多指手抓持稳定性分析[J].高技术通讯,2022,32(03):303-313.

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基于毫米波雷达点云的人体活动识别研究

关键词

毫米波雷达；人体活动识别；跌倒检测；神经网络

摘要

人体活动识别技术是人机交互中的重要环节。毫米波雷达传感器具有保护用户隐私且不受光线影响的优点，并且采集的点云数据可以描述人体形状。因此基于毫米波雷达点云的人体活动识别研究具有重要意义。

近年来随着深度学习在该领域的推广，数据集成为限制模型泛化能力的主要因素。除此之外，像跌倒这类特殊人体活动不存在固定模式，实验环境下得到的神经网络模型由于实时性、系统性和有效性等问题难以在真实的复杂环境下部署。针对目前研究中存在的问题，本文基于毫米波雷达点云进行人体活动识别研究。具体工作如下：

1.提出了一种针对毫米波雷达点云的数据增强框架，并设计了针对人体活动识别的神经网络模型。获取数据后进行活动分割，通过数据增强框架扩充数据集后对点云进行预处理实现规格统一，将连续帧体素和聚合体素作为特征输入网络模型进行分类。基于公开数据集和数据集开源团队提出模型进行实验，数据增强框架和本文模型分别将准确率提高 2.82%和 2.06%。之后基于自建数据集进行实验。算法模型对比实验中，本文模型准确率为 96.72%，远高于常见模型。在不同维度下数据增强框架效果对比实验中，使用数据增强框架至少带来 12%的准确率提升。

2.提出了一种基于特征分析的跌倒检测算法，通过有效目标划分和动态目标追踪进行预处理，提取时序点云数据的特征后进行跌倒检测。该算法具有低复杂度的优点，可以部署在嵌入式端且不需要进行数据训练。

3.构建了包含前后端的实时跌倒检测系统，传感器接收回波信号后，通过嵌入式端进行跌倒检测并将结果通过无线传输模块上传至云端服务器，手机客户端通过订阅接收消息。在动态目标追踪实验中平均距离误差和最大距离误差分别小于 0.1m 和 0.3m。在长时间复杂场景监测下，跌倒检测精确率和召回率分别达到 96.6%和 97.2%，高于对比系统。

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(a) 示意图　　(b) 实物图

图 4.24　红外光学运动捕捉设备

NOKOV 度量动作捕捉在研究中的应用摘录

为验证基于恒加速度模型的动态目标追踪算法在多人场景下的准确性，选用图 4.24 所示 NOKOV 生产的红外光学运动捕捉系统作为真实数据基准。

引用格式　王智铭.基于毫米波雷达点云的人体活动识别研究[D].浙江大学，2023.DOI：10.27461/d.cnki.gzjdx.2023.001674.

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基于机器视觉和倾角传感器的位姿检测系统及验证

关键词

位姿检测；机器视觉；参数优化；自动标定；支持向量机

摘要

在未来几年内,煤炭在我国的能源体系中仍然处于主体能源地位。煤矿井下综掘工作面的自动化可以大幅提高生产效率。目前,我国井下综掘工作普遍以悬臂式掘进机单巷掘进为主,因此悬臂式掘进机位姿检测是综掘工作面自动化的基础和前提。只有获取稳定可靠的掘进机实时位姿,才能够在此基础上进行综掘工作面自动化、智能化改造工作。本文提出一种基于机器视觉和倾角传感器的悬臂式掘进机位姿检测方法,针对位姿参数求解、激光标靶参数优化、激光标靶自动标定、激光光点目标识别等技术展开研究,具体研究内容与工作成果如下:

提出基于机器视觉和倾角传感器的悬臂式掘进机位姿检测系统总体方案,制作了室内实验样机和车间实验样机,并设计了位姿检测软件系统。在总体方案的基础上进行井下综掘工作面建模分析,推导出五个位姿参数逆解的计算公式。

针对位姿检测系统不脱靶工作条件和实际应用中激光标靶小体积需求,使用遗传算法进行激光标靶参数优化,由对称性原则简化了优化参数,并且对位姿组合进行分析,简化约束方程以提高算法效率,通过正运动学仿真和多次优化数据对比验证了优化算法的有效性。

机器视觉部分使用张正友标定法进行相机内外参数标定和畸变校正,并在此基础上提出基于棋格盘标定板的激光标靶自动标定方法,减小了测量模型与理论模型的尺寸差异导致的测量误差。基于背景差分法的动态目标检测方法对激光光点目标进行检测,通过图像预处理手段滤除源图像中的弱干扰,基于 HOG 特征的支持向量机分类器进行强干扰情况下的激光光点目标识别。对激光光点目标进行中心定位,得到激光光点中心的像素坐标。

进行一系列的实验设计与数据分析。通过倾角传感器数据滤波实验验证了卡尔曼滤波方法在倾角传感器实时角度测量过程中的必要性和有效性。通过室内实验得到位姿检测系统的角度测量误差和偏距测量误差,证明了系统可以满足测量精度要求。通过车间实验得到了不同干扰条件下,图像处理模块对激光光点目标的识别率和处理时间,证明了系统具有良好的可靠性和高实时性。

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(a) 机械振动台及倾角传感器

(b) NOKOV 测量系统

图 5.2 倾角传感器实验设备

NOKOV 度量动作捕捉在研究中的应用摘录

1.3 本文主要研究内容

（5）第五章：位姿检测系统实验设计与验证。本章首先进行倾角传感器数据滤波实验，使用卡尔曼滤波器对其源数据进行滤波，验证卡尔曼滤波的有效性。然后在室内实验中，以 NOKOV 光学三维动作捕捉系统为测量基准，与位姿检测系统的测量结果进行对比，证明系统的测量误差小，可以满足测量精度要求。最后在车间实验中，重点测试了在不同干扰条件下，图像处理模块对激光光点目标的识别率和处理时间，证明了系统具有良好的稳定性和高实时性。

2.3 实验样机平台搭建

实验内容主要包括两个环境下的实验，即室内实验和车间实验。室内实验的主要目的是以 NOKOV 光学三维动作捕捉系统（以下简称为" NOKOV 测量系统"）为基准，获取实验样机的实时位姿数据，再将本文所设计的位姿检测系统得出的实时位姿数据与其进行对比，进而对位姿检测系统进行理论验证及精度分析。

5.1 引言

本章将基于第二章设计的两款实验样机平台对位姿检测系统进行一系列的实验设计与验证。在室内环境下，同时使用 NOKOV 测量系统和本文所设计的位姿检测系统对室内实验样机进行实时位姿检测，将两组位姿数据进行对比，以验证位姿检测系统可以满足测量精度要求。在车间环境下，车间实验样机将安装于 EBZ-160M 型悬臂式掘进机上，控制悬臂式掘进机进行前进、后退、左转、右转等动作，同时添加部分强干扰，以验证位姿检测系统的抗干扰性和识别率。

5.2.2 实验设计与验证

实验过程中使用到的设备有：机械振动台、振动信号控制器、功率放大器、笔记本电脑、倾角传感器、电源以及 NOKOV 测量系统，实验设备如图 5.2 所示。 NOKOV 测量系统技术参数如表 5.1 所示

引用格式 张世雄. 基于机器视觉和倾角传感器的位姿检测系统及验证[D].西安电子科技大学，2021.DOI：10.27389/d.cnki.gxadu.2021.000178.

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基于激光灯塔的合作航天器位姿测量方法及其精度分析

关键词

相对位姿测量；激光灯塔；旋转激光扫描；PnP 问题；精度因子

摘要

针对现有合作航天器相对位姿测量手段存在不能较好兼顾视场范围和精度、缺乏简单有效的精度评价指标的问题，提出一种基于激光灯塔的合作航天器相对位姿测量方法，能够兼顾视场与精度，并提出了该方法的精度评价指标。激光灯塔系统通过激光发射站和若干光电传感器测角实现相对位姿测量。根据激光灯塔测角原理，给出了该方法的 PnP 位姿解算算法；针对位姿测量精度分析问题，建立 PnP 问题测角误差传播模型，提出了位姿测量精度因子作为精度评估指标。实验表明，激光灯塔系统的姿态、位置测量精度量级分别为 0.1°、毫米级；精度因子模型估计结果与测量精度实测结果存在一致性规律，可快速评估测量精度，指导传感器布局优化。此外，建立的测角误差传播模型也适用于视觉等涉及 PnP 问题的测量系统。

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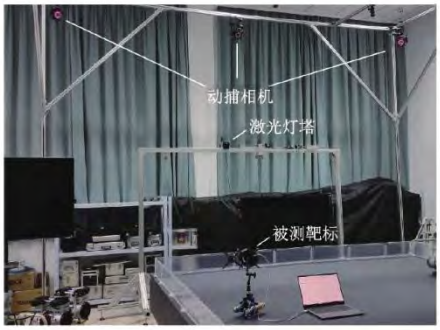

图 4　位姿测量精度测试

Fig. 4　Measurement of pose measurement precision

NOKOV 度量动作捕捉在研究中的应用摘录

实验中使用 NOKOV 公司的动作捕 捉系统，数据刷新率为 60Hz，实测对被测靶标(图 2(b)) 的姿态测量精度在 0.01°量级，位置测量精度为亚毫米级，其测量精度满足作为真值的要求。

引用格式 陈汉瑜,武俊峰,康国华等.基于激光灯塔的合作航天器位姿测量方法及其精度分析[J].仪器仪表学报,2023,44(12):101-110.DOI:10.19650/j.cnki.cjsi.J2311957.

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基于计算机视觉的下肢运动检测系统设计

关键词

计算机视觉；下肢运动；下肢运动检测；运动数据解算；OpenPose 模型

摘要

目的：设计基于计算机视觉和人体关键点检测神经网络模型的人体下肢运动检测系统，以非接触的方式实现三维空间中的人体下肢运动情况检测。方法：首先，搭建运动数据采集平台，获取人体下肢运动图像，并基于 OpenPose 神经网络模型提取每一帧图像中下肢关键点的二维图像坐标。其次，结合运动数据采集平台中的视觉传感器的位姿信息，基于计算机视觉算法解算关键点的空间坐标，解析三维空间中的下肢运动情况。最后，以骑行运动为例、以动作捕捉系统同时采集的运动数据为标准，分析该系统在不同运动速度时的数据解算情况。结果：骑行速度为 0.8、1.3、2.1m/s 时，该系统解算的数据和动作捕捉系统获得的数据的皮尔逊相关系数分别为 0.950、0.917、0.828，均在强相关范围内。结论：该系统解算的数据可反映下肢运动情况，对三维空间的下肢运动检测有一定效果。

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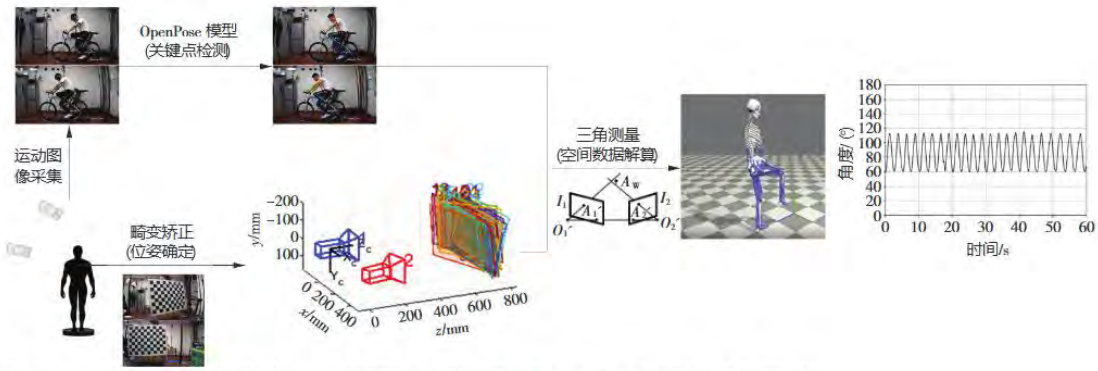

注：O_1'、O_2' 为左右 2 个摄像头的光圈中心，I_1、I_2 为成像平面，A_W 为现实世界的点，A_1'、A_2' 为 A_W 对应于 2 个成像平面的点。

图 1　下肢运动检测系统设计整体流程图

NOKOV 度量动作捕捉在研究中的应用摘录

首先搭建运动数据采集平台，包括用以录制下肢运动视频的 2 个视觉传感器（即 RGB 摄像头）、1 台台式计算机、室内动感单车骑行平台、用以验证运动数据的 NOKOV 动作捕捉系统。NOKOV 动作捕捉系统包括 12 个动作捕捉镜头、POE 交换机、动作捕捉数据处理软件 Seeker。动作捕捉系统通过记录贴在人体关节上的 Marker 点（反光标识点）的运动轨迹解析人体运动数据，镜头布置如图 2 所示。

引用格式 张钰佳，王伟，秦涵书等.基于计算机视觉的下肢运动检测系统设计[J].医疗卫生装备，2024,45（02）：22-27.DOI：10.19745/j.1003-8868.2024024.

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基于可见光的煤矿井下定位技术研究

关键词

煤矿井下定位；可见光定位；人员监测；调制发射器；未调制发射器

摘要

煤矿井下定位技术在矿井安全开采、人员监控调度以及井下灾后救援中起着重要作用。由于井下环境复杂、技术难关受限,井下目标的无线定位效果并不理想。可见光具有多径效应小、无电磁效应、抗电磁干扰等优势,同时井下的照明设备随处可见,因此新兴的可见光定位技术为井下定位提供了一种新思路。然而,目前井下可见光定位技术的研究尚不完善,存在许多不足之处。为进一步发挥可见光定位技术在井下环境中的优势,本文从可靠性、适用性和实用性三个角度出发,对基于可见光的煤矿井下定位技术开展研究。

⑴针对传统井下可见光定位技术中收发器部署方式存在的光信号接收不可靠的问题,研究基于收发器反转机制的井下可见光定位方法。利用矿工头灯作为发射端,构建可见光定位与惯性导航相融合的井下定位模型,设计面向井下特殊环境的可见光闪烁频率选择与识别算法,提出频率功率追踪算法来最小化可见光基站的定位误差,制作即时闪烁特定频率的专用矿灯,有效提升可见光定位技术在井下环境中的可靠性。

⑵针对传统井下可见光定位技术使用调制发射器导致系统在井下部署困难、硬件改造成本高的问题,利用可见光未调制发射器,研究基于旋转编码机制的井下可见光定位方法。通过极坐标表示目标位置,设计朗伯余弦定律与旋转编码相结合的距离计算方法,给出基准线位置与旋转编码相结合的夹角计算方法。实验结果验证了本方法的优越性,只利用原始 LED 灯也能达到较高的定位精度。

⑶在上述研究基础上,进一步研究基于可见光定位技术的井下人员安全监测方法。针对井下罐笼门非密闭而存在的安全隐患,设计光强阈值监测算法实现罐笼人员肢体定位功能,利用可见光闪烁频率分离算法实现罐笼超载监测功能,利用可见光闪烁频率识别算法实现罐笼人员打卡功能,提出罐笼安全区域划定方法实现罐笼安全区域监测功能。实验表明本方法监测准确率在 96%以上。

综上,本文从可靠性、适用性和实用性三个角度出发对基于可见光的煤矿井下定位技术开展研究,分析目前井下可见光定位技术存在的一些问题,并且提出相应的改进方法。同时,本文利用所设计的可见光发射端和接收端在井下巷道实验室等环境中进行了大量实验,实验结果验证了本文所提出方法的有效性。该论文有图 62 幅,表 9 个,引用格式 86 篇。

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图 3-22 系统定位误差实验场景

Figure 3-22 Experimental scenario of system positioning errors

NOKOV 度量动作捕捉在研究中的应用摘录

实验场景如图 3-22 所示。本章使用 NOKOV 动作捕捉系统来定位矿工的实时位置作为真实值，该动作捕捉系统由四个光学动作捕捉镜头和一些涂有特殊荧光材料的反射标记组成，可以在 12m× 12m 的区域内实现亚厘米级的室内定位精度。在实验过程中，将反射标记部署在调制矿灯上，同时将运动捕捉系统确定的反射标记的位置作为参与者的真实位置。图了-23 绘制了由动作捕捉系统监测的真实轨迹和系统的预测轨迹。可以计算出矿工的平均误差在 10cm 左右，表明了所提出井下定位方法有着较高的精度。

引用格式 庞明智. 基于可见光的煤矿井下定位技术研究[D]. 中国矿业大学,2022.DOI:10.27623/d.cnki.gzkyu.2022.001031.

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https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C475KOm_zrgu4lQARvep2SAkaWjBDt8_rTOnKA7PWSN5MHDwwCDmxNIU0Nn4iFVvXhNhqfCuGkhcOfQ8YTTXRSfd&uniplatform=NZKPT

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基于零速修正的单兵自主导航方法研究

关键词

单兵自主导航；MIMU；零速区间；零速修正；扩展卡尔曼滤波

摘要

单兵在我国国防安全等多方面发挥着重要作用,导航能力是单兵执行任务的关键基础,因此单兵导航技术备受关注。近年来,为解决复杂及未知环境下,外界信息可依赖性差的难题,基于 MIMU 的单兵自主导航技术得到了快速发展。零速修正是一种可有效抑制因 MIMU 漂移严重等导致系统误差发散的方法。然而传统零速修正算法对不同单兵及不同运动状态的适应性较差。因此,本文针对单兵作战特征及其导航需求,对零速修正中的关键技术进行了研究并实现了优化改进,提出了基于零速修正的单兵自主导航方法,并通过试验验证了所提方法的可行性。主要研究内容及相关工作如下:首先,梳理分析了单兵自主导航技术的国内外研究现状。从核心层、基础层、应用层及拓展层四个层次对基于 MIMU 的单兵自主导航技术的发展进行了剖析总结；从零速区间检测及零速区间误差校正两个方面对零速修正技术的发展做出了分解阐述。其次,对单兵自主导航原理进行了系统性的研究,从惯性导航基础入手,对比分析了两种常用的基于 MIMU 的单兵自主导航方法,重点阐述了零速修正方法,并从零速区间检测及零速误差校正两方面对其算法进行了研究。然后,针对单兵实际作战情况及导航应用需求,提出并实现了一种基于 MIMU 的单兵自主导航系统搭建方法。采用 ATK-IMU901 等设备搭建了单兵自主导航系统,设计并进行了实时性、有效性及适用性测试试验,试验结果表明该系统具有较强的实用性。接着,针对阈值判断法存在着受传感器噪声影响较大、性能因运动状态改变而下降的问题,提出了一种基于 Mahony-PSVT 的零速区间检测算法,试验结果表明不同试验者在不同运动状态下,该算法零速区间平均单步误判率均低于 10%,相较于广义似然比检验算法提升约 30%,具有较好的广泛适用性及准确性。最后,针对单兵自主导航系统中初始对准误差、数据采集误差等会随时间累积的问题,提出了一种基于扩展卡尔曼滤波的零速误差校正算法,试验结果表明其定位误差为 1.17%,能够满足单兵导航需求,具有较高的可靠性。

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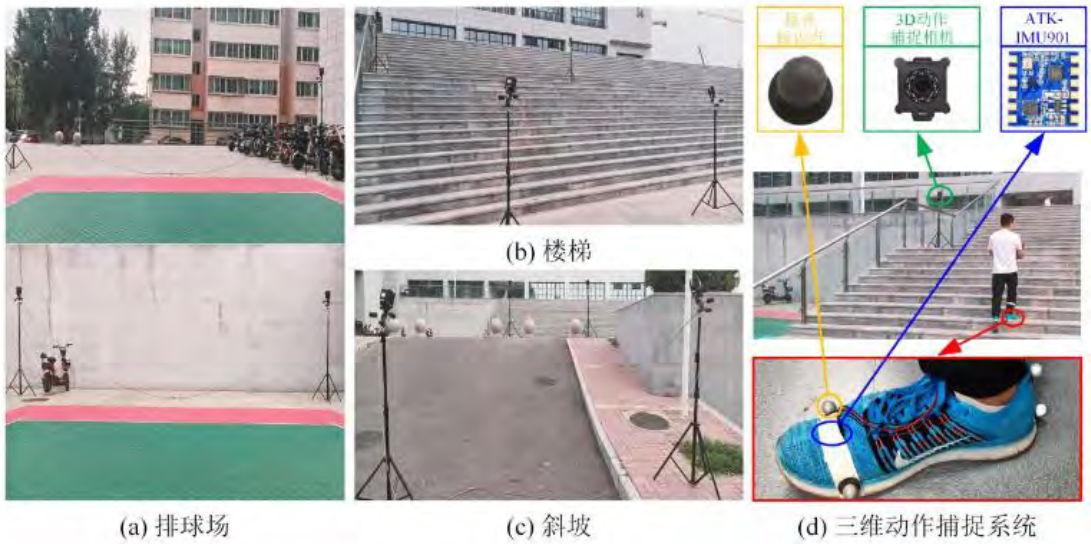

(a) 排球场 (b) 楼梯 (c) 斜坡 (d) 三维动作捕捉系统

图 3-10 利用光学三维运动捕捉系统获取试验的真实参考

NOKOV 度量动作捕捉在研究中的应用摘录

为了真实准确的评估本文所提算法的零速检测效果，本文基于光学三维动作捕捉技术实现试验者运动的采集，并将其结果作为试验的真实参考。光学三维动作捕捉技术其工作原理可简述为将特定光点/标签固定于运动目标，利用相机对光点/标签进行监视跟踪，从而实现运动的捕捉。当相机以足够高的速率连续拍摄时，可以从图像序列中获得点的轨迹。具体试验中，本文使用了北京度量科技有限公司（NOKOV）研发的光学三维动作捕捉系统，如图 3-10 所示，该系统主要包括动作捕捉相机、光学标定系统、反光标识点（也称为"反光标识球"、"Marker"）等。

引用格式 杨燕栋. 基于零速修正的单兵自主导航方法研究[D]. 中北大学,2023.DOI:10.27470/d.cnki.ghbgc.2023.000957.

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基于煤岩界面识别的采煤机智能调高控制方法研究

关键词

采煤机；煤岩界面识别；轨迹优化；智能控制；

摘要

煤岩界面识别及采煤机自动调高作为采煤机智能化的关键技术，是实现采煤工作面的智能化、无人化的重点和难点。实际工作中，多采用人工观测或结合多种方法进行煤岩界面的识别，采煤机通过记忆截割方式和 PID 控制等控制方法进行调高控制，无法适应煤层的复杂变化，且控制算法精度有限。针对采煤机的智能化调高作业问题，本文利用低频超宽带电磁波雷达，采用基于斜投影算子的类最大似然信号定位方法进行煤岩界面识别，得到煤岩界面轨迹；考虑具体工况要求，以最大回采率为优化目标，基于有约束优化算法，进行截割轨迹优化；基于采煤机运动学和状态空间模型，采用基于新型神经网络观测器的间接自适应规定性能控制方法，实现采煤机自动调高控制。最后，通过试验验证所提方法的有效性和优越性，为采煤机智能化提供技术支撑，试验结果表明，摇臂转角轨迹跟踪误差百分比约不超过 8.2%，截割轨迹最大高度误差约不超过 0.01 m。

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NOKOV 度量动作捕捉在研究中的应用摘录

本试验中，使用 NOKOV 红外动捕系统实时捕捉采煤样机调高摇臂 上反光标识点位置，从而实时获得真实截割滚筒轨迹。

引用格式 刘送永，程诚，吴洪状等.基于煤岩界面识别的采煤机智能调高控制方法研究[J].煤炭科学技术，2024,52（S2）：186-200.DOI：10.13199/j.cnki.cst.2022-0004.

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https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C45S0n9fL2suRadTyEVl2pW9UrhTDCdPD64qs7f09ap5B8IhqhhRXvZ8BKQOc5jK2bODZ4sVunzjOb3d-49oRWo_&uniplatform=NZKPT

基于序列图像学习的巷道掘进机定位方法研究

关键词

机器鳄鱼；步态规划；动作捕捉；运动稳定性；运动仿真

摘要

煤矿综掘工作面受限于狭小空间、工艺繁杂、环境恶劣等特殊条件，导致用工多、安全性差、效率低等问题，亟需研发更加安全高效的智能化掘进技术与装备。巷道掘进机作为综掘工作面的核心设备，对其智能化进行研究具有重要的社会价值和经济意义。为了实现巷道掘进机的智能化作业，首先需要解决的关键问题为掘进机机体定位，精确、鲁棒的机体位姿检测方法是保障巷道智能掘进有效性的首要条件。因此，本文针对巷道掘进机机体定位问题，提出了一种基于时间序列图像学习的机体绝对六自由度位姿实时检测方法。首先，通过在掘进机机体安装一台单目相机，并在掘进机后方设置人工特征对象，设计适用于巷道狭长、非结构化环境的视觉定位方案。然后，提出用于时间序列图像融合的深度学习模型，其中，使用一种训练好的多尺度变分自编码器辅助的卷积神经网络（MSVAE-CNN）的编码器模型提取时间序列图像中每个样本的多尺度潜在空间特征，以保证图像特征提取的鲁棒性；基于双向长短期记忆（LSTM）网络构建时间序列图像特征融合模型，并同时估计所有时间步图像样本对应的机体位姿参数，当推理某个时间步图像对应的位姿参数时，其他时间步的信息都可作为先验知识，通过学习图像样本之间的特征相关性，提高位姿估计的精度和可靠性；另外，使用多头自注意力机制进一步提高特征融合性能，使用张量训练分解压缩模型，实现在轻微损失位姿估计精度的前提下大幅降低模型参数数量。最后，基于一辆履带小车进行试验研究，使用 NOKOV 红外动捕系统获取小车机体实际位姿，试验结果显示，所提方法对中心偏距和方向角的估计平均绝对误差分别约为 25mm 和 0.36°，完全能够满足巷道掘进机的定位需求，并且定位精度明显优于 MSVAE-CNN 模型，验证了所提出的基于序列图像学习的机体定位方法的有效性与高性能。

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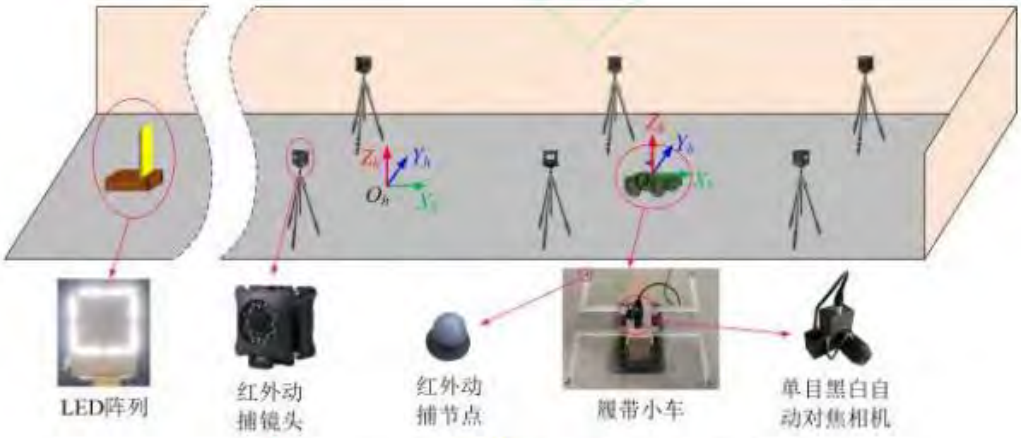

图 6 试验数据获取系统布置

Fig. 6 Deployments of the dataset acquisition system

NOKOV 度量动作捕捉在研究中的应用摘录

本文使用在文献\[16]中获取的数据集验证本文所提出的模型，其是以一辆履带小车为相机载体，使用 NOKOV 红外动捕系统获取小车机体实际位姿得到的，如图 6 所示。为了应用于本文所提出的基于时间序列图像融合的位姿估计模型， 需要将数据集中的每一条数据转化为步长为 5 的时间序列，首先随机选取 280 个数据位置，每个位置连续取间隔为 2 的 5 个样本，共取出 1400 个样本（ 280 条时间序列样本）作为测试数据集， 剩余数据作为训练数据集。在训练集中，每个图像样本及其对应的位姿标签都被作为第一个时间步的训练数据，并以间隔为 1、2 或 3 取连续 4 个样本构成时间序列，若其后不足 4 个样本，则删除该条数据，共生成 6826 条训练数据。在划分好训练集和测试集后，基于文献\[16]中的方法，使用训练集数据训练 MSVAE-CNN-S3 模型以提供 PTE 模型。

引用格式 吴洪状,程诚,刘送永.基于序列图像学习的巷道掘进机定位方法[J].煤炭学报,2023,48(S2):778-789.DOI:10.13225/j.cnki.jccs.2022.1272.

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基于旋转天线阵列的室内定位算法研究

关键词

信道状态信息；旋转天线阵列；室内定位；深度学习

摘要

室内定位是当前研究热点。Wi-Fi 技术作为无线局域网的代表技术，具有覆盖范围广、成本低廉的特点，被广泛应用于室内环境，可以在数据通信的同时提供位置信息。然而由于室内环境的封闭性与复杂性，现有的室内 Wi-Fi 定位方法存在相位校准复杂、指纹库构造成本高、定位分辨率低等问题，难以满足实际应用需求。因此，本文深入分析了 Wi-Fi 物理层信道状态信息（Channel State Information, CSI）的定位机理，开展基于旋转天线阵列的室内定位方法研究，主要研究内容如下：

（1）针对 CSI 相位校准复杂的问题，提出了一种基于旋转天线阵列的到达角（Angle of Arrival, AOA）定位算法。首先，构建旋转天线阵列的 CSI 相位差模型，利用无线网卡时钟频率和下采样频率相同的特性消除 CSI 相位偏移。进一步，设计了 CSI 相位差优化方法，对相位差进行解缠绕、去噪和子载波筛选，提高 AOA 估计的精度。最后，分析旋转阵列天线物理位置与 CSI 相位差变化率的映射关系，实现无需相位校准的位置估计。

（2）为降低室内多径效应影响，解决指纹数据库构建成本高的问题，设计了一种基于双流特征融合神经网络的 AOA 估计修正模型 FusionRotation。首先，利用卷积神经网络分别提取到达角序列和 CSI 商矩阵中隐含的时空信息并进行特征融合，然后使用注意力机制降低融合特征冗余。最后将定位任务从常规的分类问题转换为回归问题，对 AOA 估计结果进行修正。该方法在离线训练阶段无需构建细粒度网格指纹库，仅使用少量位置样本便可实现室内鲁棒定位。

综上，本文提出了基于旋转阵列的室内定位算法，并使用旋转平台、部署有 Atheros-CSI-Tool 的 TL-WDR4310 路由器、遥控车、NOKOV 三维光学动捕摄像头等设备搭建了室内定位原型系统。在室内实验室与地下巷道两个场景中对算法的定位性能、旋转速度、序列长度等参数进行实验评估，结果表明本文所提出的算法显著优于现有算法。

该论文有图 47 幅，表 4 个，引用格式 87 篇。

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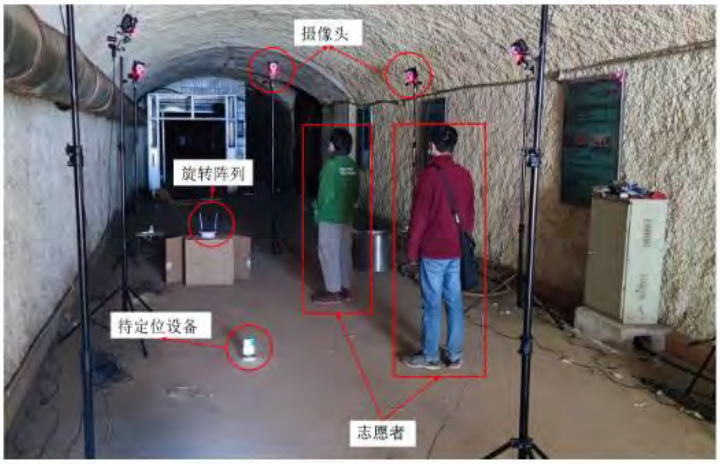
（a）室内实验室



（b）地下巷道

图 3-12 实验场景

Figure 3-12 Experimental scenarios

NOKOV 度量动作捕捉在研究中的应用摘录

使用八个 NOKOV 三维光学动作捕捉摄像头用于测量真实值，实验设备如图 3-13 所示。

引用格式 张铁洋.基于旋转天线阵列的室内定位算法研究[D].中国矿业大学，2023.DOI：10.27623/d.cnki.gzkyu.2023.002540.

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基于循环神经网络的运动目标轨迹预测

关键词

运动目标；轨迹预测；混合高斯模型；循环神经网络；多层网格搜索

摘要

运动目标的抓捕和拦截技术在军事、航空航天、工业生产、体育运动等多个领域有广泛的应用,而对运动目标进行识别、定位和轨迹预测是完成对其抓捕和拦截的基础和前提。传统的识别、定位方法对环境依赖性强；传统的轨迹预测方法主要基于运动学模型,泛化能力较差。因此,本文采用深度相机获取场景深度图像,基于混合高斯模型的背景差分法实现运动目标的实时识别与定位;采用环境适应性好、泛化能力强,适用于时间序列预测的循环神经网络方法（Recurrent Neural Network,RNN）,开展运动轨迹预测相关研究。完成的主要工作有: (1) 系统平台搭建。采用 Kinect 深度相机和 NOKOV 动作捕捉系统搭建系统硬件平台,采用 ROS（Robot Operating System）系统作为机器人的软件平台；并对系统进行标定,包括 Kinect 深度相机的内参标定,以及 Kinect 与 NOKOV 动作捕捉系统的联合标定。（2）运动目标识别与定位。采用基于混合高斯模型的背景差分法对运动目标进行识别；对运动目标进行相平面定位以获取对应像素点的点云信息,采用高斯牛顿法拟合点云质心获取运动目标的空间坐标；结合卡尔曼滤波对质心运动轨迹进行优化,将目标定位误差由 13mm 下降到 10mm。（3）运动目标轨迹预测网络搭建。采用基于 RNN 的运动目标轨迹预测方法,搭建长短时记忆（Long Short Term Memory,LSTM）网络模型；采用基于多层网格搜索的模型参数优选算法对网络模型的步长 L、隐藏节点个数 H 和学习率η进行优选；最后,采用随时间反向传播算法（Back Propagation through Time,BPTT）对 LSTM 网络模型的权重参数进行优化训练。（4）运动目标轨迹预测实验与结果分析。首先对模型关键参数进行优选,确定模型步长 L、隐藏节点个数 H 和学习率η分别为 25、50 和 0.07；然后进行运动目标轨迹预测对比实验,分别采用标准 RNN 模型,LSTM 模型及 GRU 模型对运动物体轨迹进行预测,并对比三种模型的预测精度,结果分析表明:在预测运动目标轨迹落点时,标准 RNN 模型不能做出有效预测,LSTM 模型的预测精度较 GRU 模型提高了 45.36%；最后将所搭建网络应用于不规则运动目标乒乓球拍的轨迹预测中,证明了所搭建网络的泛化能力。

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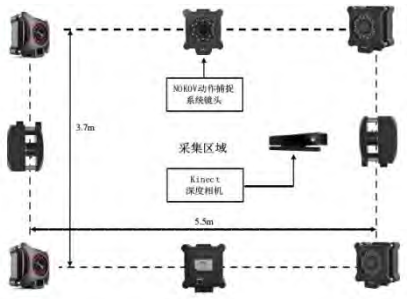

图 2.2 硬件环境

NOKOV 度量动作捕捉在研究中的应用摘录

本章根据运动目标识别与轨迹预测的实际需求，搭建系统平台，包括硬件平台与软件平台的搭建。为获取相机内参矩阵，对 Kinect 深度相机进行标定；为后续对定位结果进行验证，对 Kinect 与 NOKOV 动作捕捉系统进行联合标定。
本文在实验室环境中将空间目标简化为质量均匀的球形物体且运动状态只受空气阻力和重力影响，获取其实时位置并进行轨迹预测。系统整体框架如图 2.1 所示，首先使用 NOKOV 动作捕捉系统采集完整的轨迹数据集对 LSTM 循环神经网络进行训练和测试，然后在 ROS 环境下搭建运动目标识别与定位系统，订阅 Kinect 深度相机发布的深度图像，对运动目标进行识别与定位，最后将运动物体三维坐标输入训练好的网络以完成轨迹预测。
在实验室环境下，搭建硬件环境如图 2.2 所示，其中包括八个 NOKOV 动作捕捉系统镜头和一个 Kinect 深度相机，整个场景大小为 5.5m×3.7m。Kinect 深度相机采集深度图像并将其发布出来以供软件系统订阅与处理， NOKOV 动作捕捉系统采集训练数据对轨迹预测网络进行训练。
NOKOV 动作捕捉分析系统是用于精确捕捉和采集运动物体在三维空间运动数据的高性能设备，其采用领先的被动式光学动作捕捉技术，基于多目立体视觉测量原理，结合计算机图像处理和先进算法，把目标物体上标志点的动作转化为数据。即将标记点安置在目标物体的各个部位，由多部近红外高感度摄像机同步实时捕捉运动信息，然后将信息进行数字化处理，得到三维坐标信息，再结合时间参数，计算相应的运动学参数，如位移、速度、加速度、角度、角速度等，实现对目标物体运动状态的定量分析和全方位六自由度的精确测量。

引用格式 杨明辉.基于循环神经网络的运动目标轨迹预测[D].武汉大学,2019.

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基于蚁群优化算法引导深度 Q 网络的移动机器人路径规划算法

关键词

移动机器人;路径规划;深度 Q 网络算法;蚁群优化算法;强化学习;算法优化;

摘要

针对移动机器人深度 Q 网络(Deep Q-Network, DQN)路径规划算法在处理大规模复杂未知环境时收敛速度慢、规划路径差等问题，提出一种结合蚁群优化(Ant Colony Optimization, ACO)算法与 DQN 的路径规划(Ant Colony Optimization Guide DQN,ACOG-DQN)算法。引入 ACO 的信息素机制，以有利于到达终点为目标对当前可能路径进行选择，在降低对环境无效探索次数的基础上确定最优路径；对先前路径选择经验利用阈值筛选，形成样本集对 Q-network 进行训练，利用 Q-network 确定当前环境下的移动机器人最优路径。以 ACO 和 Q-network 分别确定的最优路径以及随机探索确定的最优路径为候选，设计 Q-network 最优路径权重随时间增大的路径选择机制进行决策，遴选出当前动作，达到路径最终由 Q-network 完全决策的目标。3 组不同复杂环境下的仿真与实体试验结果均表明，新的 ACOG-DQN 算法相对于 DQN 算法，在收敛速度、路径质量和算法稳定性方面表现出更优的性能，表明了新算法的有效性。

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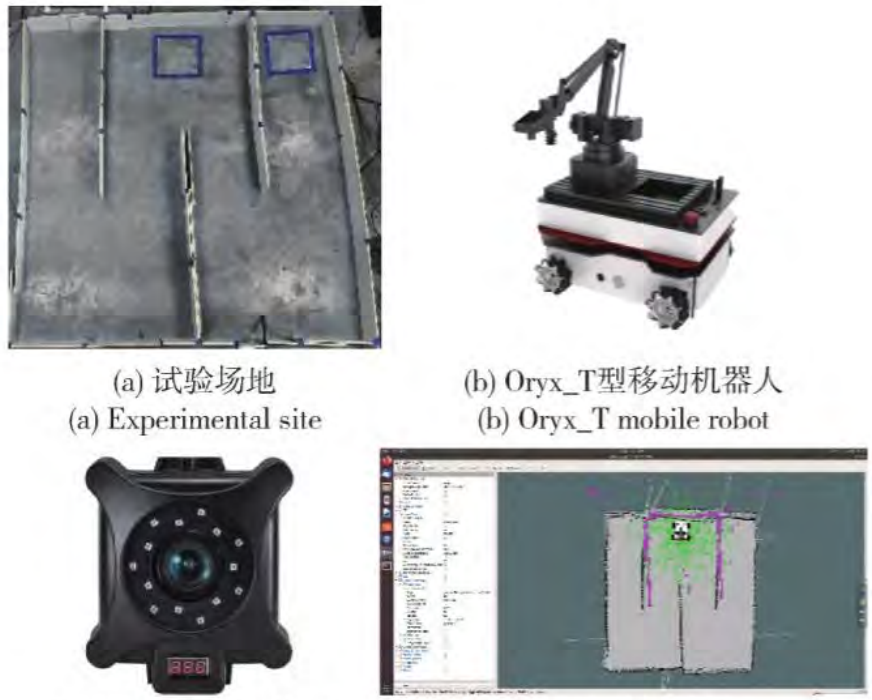

(a) 试验场地
(a) Experimental site

(b) Oryx_T型移动机器人
(b) Oryx_T mobile robot

(c) Mars动作捕捉相机
(c) Mars motion capture camera

(d) Rviz地图建模
(d) Rviz map modeling

图 17　硬件与软件条件

NOKOV 度量动作捕捉在研究中的应用摘录

> *4 实体试验与分析*
> *为了验证 ACOG-DQN 算法在真实移动机器人上的应用效果，本文搭建图 17(a)所示 4m × 4m 的特殊回廊地形地图，基于开源机器人操作系统 R OS(Robot Operating System)，使用图 17(b)所示的元创兴科技 Oryx_T 型移动机器人作为算法载体，利用 NOKOV 度量光学三维动作捕捉设备为移动机器人提供三维实时定位，并捕捉记录路径轨迹。*

引用格式 李海亮,李宗刚,宁小刚,等.基于蚁群优化算法引导深度 Q 网络的移动机器人路径规划算法[J].兵工学报,2025,46(11):65-78.

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基于因子图的人车协同导航算法

关键词

行人导航；协同导航；可观测度分析

摘要

行人导航系统，又称单兵导航系统或者个人导航系统，是一种可穿戴式导航设备。使用惯导解算原理的行人导航系统，常常采用基于微电子机械系统（Micro Electro Mechanical System / MEMS）的惯性测量单元（Inertial Measurement Unit / IMU）来实现。受限于目前微机电技术的发展，基于 MEMS 技术的 IMU 精度较低，导航误差会快速积累。如何降低误差、提升导航精度是行人导航领域的热门问题。协同导航是一项新兴的导航方法，常用于多智能体系统（Multi-Agent System / MAS 中。通过节点间导航状态共享、节点间信息测量或者节点位置信息及不确定性信息存储转发，协同导航技术可以在控制器件成本的前提下提高部分或全部节点的导航精度。

本文主要研究了基于零速修正的行人导航算法、基于因子图的协同导航算法以及基于李导数的协同导航可观测度分析。

围绕基于零速修正的行人导航算法，文章对行人导航系统进行了误差分析和误差建模，设计并实现了基于零速修正的扩展卡尔曼滤波算法；针对高度发散问题，融合了气压计高度信息约束高度误差；针对航向角误差问题，对地磁场测量误差进行了综合建模，在参数标定中引入异常值检测策略，通过剔除粗大误差数据提升标定精度，提出了一种基于磁场畸变率的自适应互补滤波的航向修正算法，有效减小了航向角误差。

围绕基于因子图的协同导航算法，提出了基于因子图理论的协同导航系统模型，建立了基于因子图的信息融合框架，推导出导航状态优化的代价函数，引入遗传算法对导航状态进行寻优完成信息融合。

围绕基于李导数的协同导航可观测度分析，提出了协同导航可观测度模型，分别分析了基于距离量测和角度量测下的可观测度分布用数值仿真验证了可观测度分布分析的正确性。

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图 4-7 Nokov 动作捕捉系统实物图

图 4-8 双领航者 UWB 基站实物图

NOKOV 度量动作捕捉在研究中的应用摘录

本小节通过行走实验验证本章所述基于因子图和遗传算法的协同导航算法。本实验在 Nokov 动作捕捉系统下进行，由该系统提供外部真实值信息。 Nokov 动作捕捉系统实物图如图 4-7 所示。在行走实验中，由两个 UWB 基站充当双领航者，如图 4-8 所示。在实验中，假设双领航者的位置信息实时已知，该信息由动作捕捉系统从外部提供。行人节点配备 MIMU 与 UWB 标签，可以对行人节点的机体角速度、机体加速度以及与两个领航节点间的距离进行测量，测量频率均为 100Hz 。

引用格式 黄灿.基于因子图的人车协同导航算法[D].哈尔滨工业大学，2021.DOI：10.27061/d.cnki.ghgdu.2021.003536.

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激光灯塔合作靶标传感器布局优化与位姿测量精度分析

关键词

相对位姿测量;激光灯塔;误差传播模型;构型优化;

摘要

针对航天器编队任务的合作靶标在不同传感器布局下，造成测量精度差异性较大的问题，将测量精度进行可视化分析，提出一个传感器优化的准则，以此来指导复杂环境下的光电传感器安装布局设计，保证激光灯塔良好的工作性能。本文选择测角误差和传感器安装误差进行分析建模，更加严密地建立了激光灯塔系统的误差传播模型，并提出一种 AP（角-精度）球形映射的方法，建立了传感器优化准则，用于评价传感器安装构型。仿真结果表明，激光灯塔系统测量误差均方根和推算值基本一致，其推算相对误差在 5%之内，由此验证了误差传播分析模型的正确性。此外，在传感器布局优化方面，利用提出的 AP 球形映射可视化测量精度，对位姿测量精度进行分析，并进行了实验验证，发现相对于共面构型，激光灯塔对非共面的传感器安装构型的位姿测量精度随观测视角分布更为均匀，不易出现测量误差发散情况。

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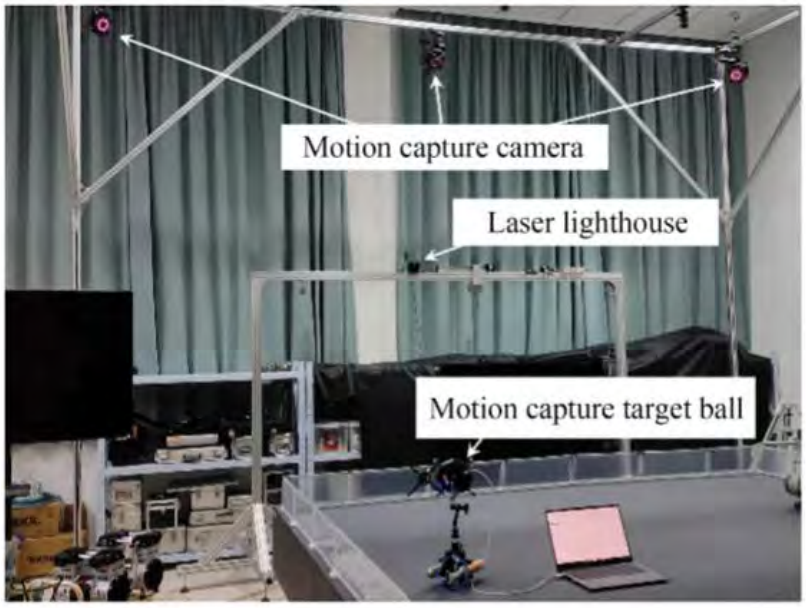

图 16　位姿测量精度测试

NOKOV 度量动作捕捉在研究中的应用摘录

5.3 实验验证分析
实验使用的激光灯塔发射站采用商用设备 HTC VIVE Lighthouse 1.0 基站。
利用合作靶标作为位姿测量实验的被测物通过靶标内部脉冲破译模块完成传感器信号的破译,并向计算机传输各传感器测角数据完成位姿解算,在合作靶标上安装多个光电传感器。
所设计的合作靶标如图 13 所示，其主体部分通过 3D 打印一体成型,设计为尺度大小 12.5cmx12.5 cmx6.25 cm 的凸多面壳体,其表面安装有 12 个光电传感器用于接收激光灯塔所发出的光信号。除了光电感应器外,为了利用动作捕捉系统测量合作目标的位姿,合作靶标还安装了 6 个可作为位姿资料真值来源的动捕靶球传感器安装构型如图 14 所示,传感器的安装布局可以保证在靶标正面各个观测视角下受到激光灯塔光照的传感器都不呈现共面分布情况，能够有效避免实验中测量误差的发散。
使用 NOKOV 公司的动作捕捉系统，如图 15 所示，动作捕捉系统配置了该公司的 Mars 系列相机，动捕相机视场覆盖范围约为 4 m×4 m，数据刷新率为 60 Hz。动捕系统合作靶标的姿态测量精度实测为 0.01°量级，位置测量精度实测为亚毫米级，其测量精度满足作为真值的要求。

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轮式机器人跟踪控制研究：模型预测控制方法

关键词

轮式机器人；模型预测控制；鲁棒控制；抗扰控制；事件驱动控制；自驱动控制；自适应预测时域

摘要

模型预测控制（Model predictive control，简称 MPC）以其优越的控制性能和强大的处理约束能力在过程控制系统中得到了广泛应用。近年来，对模型预测控制的研究在优化问题的迭代可行性，闭环系统稳定性以及在线计算复杂度分析等诸多方面取得了一系列重要成果，并且其理论已经达到相对成熟的阶段。然而，模型预测控制方法在轮式机器人的应用中尚处于研究初期，仍然存在很多重点及难点问题亟待解决。例如，如何在非完整约束以及耦合输入条件下设计终端集及相应的终端控制器；如何利用外界扰动信息来设计控制器，以保证系统的迭代可行性以及闭环稳定性，并达到一个更好的控制性能；以及如何进一步缓解模型预测控制的计算负荷以满足实时控制性能要求等。鉴于此，本论文的目的是针对轮式机器人的跟踪问题，设计实用的模型预测控制方法。本文的主要研究内容及贡献总结如下。

一、针对具有耦合输入约束的轮式机器人跟踪问题提出一种模型预测控制方法。其跟踪的方式是基于虚拟结构的，跟随者的期望跟踪位置是基于领航者机体 Frenet-Serret 坐标系下的一个虚拟结构坐标点，而跟随者的期望控制输入不仅取决于领航者的速度，也取决于分离向量。本文给出了一个领航者的控制输入应满足的充分条件，以使得跟随者在满足控制输入约束的条件下仍然能够跟踪其期望位置。基于此，为跟随者设计了一种模型预测算法，并通过设计一个菱形不变终端集及相应的终端控制器来保证算法的迭代可行性及系统稳定性。仿真结果验证了提出的模型预测控制算法的有效性。

二、在以上的研究基础上，进一步考虑外界扰动。针对受约束及有界扰动的轮式机器人的跟踪控制问题，设计两种鲁棒模型预测控制算法：基于 Tube 的鲁棒模型预测控制以及标称鲁棒模型预测控制方法。在基于 Tube 的鲁棒模型预测控制方法中，控制信号由两部分组成：一个由求解优化问题得到的最优控制量，以及一个基于实际状态与标称系统的最优状态之差设计的反馈控制律。该控制器可以使得系统的实际轨迹保持在一个以标称系统最优轨迹为中心的 Tube 内。我们证明了该算法是迭代可行的且闭环系统是输入到状态稳定的，并且通过收缩输入约束以及终端集，满足了系统约束。在标称鲁棒模型预测控制方法中，在每个采样时刻都根据当前实际状态，通过求解一个优化问题得到一个最优控制序列，然后将该序列中的第一个控制量以一种开环的方式应用于实际系统。在每一步，标称系统的状态都通过实际状态来进行更新，这进一步提供了反馈信息。通过引入一个鲁棒状态约束条件并收缩终端集，可证明算法的迭代可行性，并且系统也是输入到状态稳定的。仿真结果验证了所提出的两种控制策略的有效性。

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三、上面讨论的鲁棒模型预测控制方法，实际上是基于所有扰动实现的最坏情况设计的，其目的是牺牲一定的标称系统性能以达到尽可能好的鲁棒性能。因此，我们提出了一种抗扰模型预测控制（Disturbance rejection model predictive control，简称 DRMPC）算法，以实现存在匹配输入扰动的非完整性约束机器人的跟踪控制。基于此，设计了两种扰动观测器（Disturbance observer，简称 DOB）分别用于估计未知动态扰动以及已知谐振频率构成的扰动。通过结合扰动观测器以及模型预测控制算法，提出了抗扰模型预测控制策略。通过收缩终端集以及输入约束保证了优化问题的迭代可行性。同时，证明了如果扰动是动态未知的，那么闭环系统是关于扰动导数输入到状态稳定的；如果已知扰动的谐振频率，那么系统可达到无偏跟踪。最后，提供了仿真及实验结果以验证所提出方法的有效性。

四、考虑到传统模型预测控制方法需要非常大的计算量，我们针对非完整约束机器人的跟踪问题提出了一种事件驱动模型预测控制方法。通过根据实际轨迹以及预测轨迹的差设计一个阈值，给出了事件驱动的触发机制，其目的是减少求解优化问题的频率。然后，基于事件触发机制设计了一个模型预测控制算法。通过设计一个鲁棒终端集以及选择合适的参数，确保算法的迭代可行性。我们证明跟踪系统是实用稳定的，并给出了跟踪误差最终收敛的正不变集，该集合表明跟踪性能与最小事件间隔时间以及扰动上界是成反比关系的。仿真结果表明，计算负荷大大降低了，显示了我们提出的方法有效性。

五、上述的事件驱动模型预测控制方法可以从一定程度上缓解计算负荷，但是这种方法只降低了求解优化问题的频率，在每个更新时刻的计算复杂度依然很高。因为预测时域通常是一个常值，因此我们提出基于事件的自适应时域模型预测控制方法。首先针对一类具有加性扰动的离散非线性系统，提出一种自驱动自适应时域模型预测控制方法。在每个触发时刻，控制器可以通过求解一个优化问题给出一个最优控制序列，同时计算出下一次的触发时刻以及预测时域。通过执行这个算法，平均采样频率降低了，并且预测时域随着系统状态靠近终端集而自适应地缩短。并且，给出了与标称周期采样模型预测控制相比的一个性能损失上界，保证了优化问题的迭代可行性与闭环系统的稳定性，仿真结果验证了这种算法的有效性。然后，我们将这种方法应用到轮式机器人的跟踪问题当中，并将该方法推广为事件驱动以及自驱动的情形。算法在实验平台上进行了验证，证明了所提出的算法可以从两方面减少计算负荷：通过降低求解优化问题的频率以减少计算量，以及通过缩短预测时域来降低计算复杂度。

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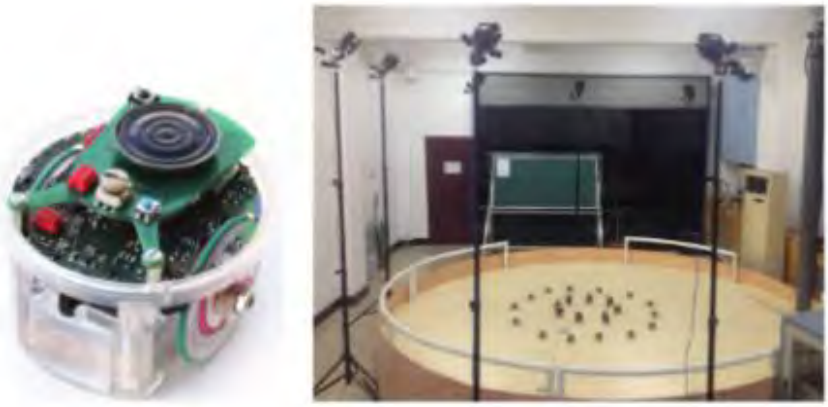

(a) E-puck　　(b) 实验平台

图 4.11 Epuck机器人以及实验平台

NOKOV 度量动作捕捉在研究中的应用摘录

4.5.2 实验验证
为了进一步证明本章提出的抗扰模型预测控制算法的有效性和实用性，有必要在真实物理系统上验证该算法。实验平台如图 4.12 所示，包含 Epuck 机器人系统和 Nokov 运动捕捉系统。

引用格式 孙中奇.轮式机器人跟踪控制研究：模型预测控制方法[D].北京理工大学，2018.DOI：10.26948/d.cnki.gbjlu.2018.000073.

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煤矿井下无设备声信号定位方法研究

关键词

煤矿井下；声信号定位；无设备定位；多目标；非视距

摘要

煤矿井下定位技术在矿井安全开采、人员监控调度以及灾后救援中起着重要作用。无设备声信号定位方法无需目标携带信号收发装置且具有无电磁效应、抗电磁干扰、廉价易部署等优势，为井下定位提供一种新思路。然而，无设备声信号定位方法的研究尚不完善，声信号传播衰减严重、可感测范围有限等问题，限制了此类定位方法在井下场景的应用。为此，本文从信号增强、多目标定位、非视距定位三个角度出发，对煤矿井下无设备声信号定位方法开展研究。

（1）针对声信号传播衰减严重、可感测范围有限的问题，本文开展基于声信号的无设备定位中信号增强方法研究。构建无设备定位声信号模型，分析影响定位信号感测距离的关键因素，提出基于位移发射信号和波束成形融合的定位信号增强方法，将位移后的发射信号与接收信号混合，增加有效带宽，并对多个麦克风采集到的信号进行加权融合，实现了信号增强的效果，增加了目标定位感测距离。

（2）针对现有井下声信号定位方案仅能对携带设备目标进行定位和跟踪，无法满足煤矿井下多个无设备目标的定位需求问题，本文开展井下多目标无设备声信号定位方法研究。提出目标多维度定位信息测定方法，通过速度信息校正声学多普勒效应导致的目标距离、角度误差，设计多维度信息融合和背景消减算法，实现多个目标的分离匹配。此外，为了更好的描述多个目标的运动状态，利用无迹卡尔曼滤波算法对采集得到的位置点进行处理，实现了井下多目标的轨迹优化。

（3）针对井下非视距场景较多、传统声信号定位方法在非视距场景下定位效果不佳问题，本文开展井下无设备声信号非视距定位方法研究。利用多目标定位技术，识别出障碍物目标和被测目标，根据基站和障碍物位置划分视距区域和非视距区域。当被测目标移动到非视距区域内时，设计基于镜像原理的非视距定位算法找到目标到基站的第一反射路径，测算目标相对巷道两侧墙壁的镜像位置，并通过镜像位置的加权融合实现了非视距场景下的目标定位。

综上所述，本文分析目前井下声信号定位方法存在的问题，从信号增强、多目标定位、非视距定位三个角度出发开展研究。同时，本文在井下巷道实验室等环境进行实验，实验结果验证了所提出方法的有效性。

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图 3-7 实验室实验场景

Figure 3-7 Laboratory experiment scene

图 3-8 井下巷道实验场景

Figure 3-8 Experimental scene of underground roadway

NOKOV 度量动作捕捉在研究中的应用摘录

实验使用 NOKOV（度量）光学三维动作捕捉系统标定真实目标位置。

引用格式 郭允天.煤矿井下无设备声信号定位方法研究[D].中国矿业大学，2023.DOI：10.27623/d.cnki.gzkyu.2023.001097.

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煤矿掘进机自定位截割控制方法及试验研究

关键词

巷道掘进机；位姿检测；轨迹跟踪控制；自定位截割

摘要

掘进机的主要功能为巷道断面截割成形，为了实现掘进机的智能化作业，首先需要解决的关键问题为掘进机机体位姿检测，精确、鲁棒的机体自定位方法是保障巷道智能掘进有效性的首要条件。在掘进机机体定位的基础上，需要对截割头进行空间定位，并设计截割头轨迹跟踪控制算法，以实现巷道断面自动精确成形。因此，本文针对掘进机自定位截割控制方法开展试验研究，首先基于齐次坐标变换矩阵法建立掘进机截割头空间运动学模型，包括机体运动学模型和截割机构运动学模型，并提出掘进机自定位截割控制策略，然后使用基于单目视觉与深度学习的掘进机机体六自由度位姿检测方法以及具有规定性能的双层模糊自适应反步控制方法，实现掘进机自定位截割，用于任意机体位姿下截割头循迹跟踪控制。在掘进机两种不同的机体位姿下进行截割头循迹跟踪控制试验，试验结果显示最大轮廓误差分别在 48mm 和 52mm（约 2.14%与 2.32%）以内，验证了所提出的掘进机自定位截割控制方法的有效性。

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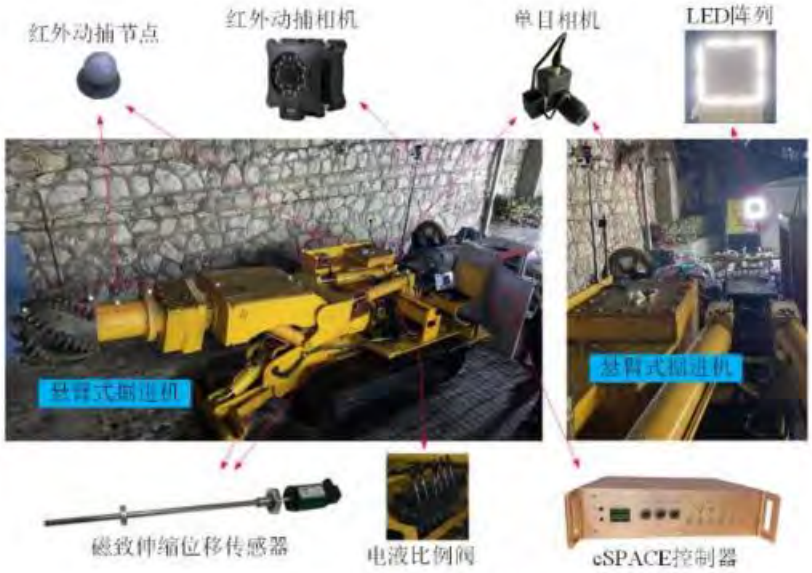

图 7 综合试验系统

Fig. 7 Integrated experimental system

NOKOV 度量动作捕捉在研究中的应用摘录

在试验过程中，使用 NOKOV 红外动捕系统获取悬臂式掘进机的机体位姿状态与截割头空间位置坐标，并将其作为真实值，其中，多个红外动捕相机安置在掘进机运动空间的四周，若干个红外动捕节点安装在掘进机机体与截割头合适的位置处。另外，红外动捕系统也为位姿估计深度学习模型的训练数据获取提供了条件。试验系统包含 4 台红外动捕相机，但为了更清晰地展示整个试验系统，只有一台显示在图中。

引用格式 刘送永,吴洪状,程诚等.煤矿掘进机自定位截割控制方法及试验研究[J].中国机械工程,2024,35(07):1318-1329.

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面向地下狭长隧道的移动机器人定位与建图方法研究

关键词

地下狭长隧道；同步定位与地图构建；超宽带定位；多传感器融合

摘要

随着移动机器人智能化、自主化程度的提升，使用移动机器人在诸如煤矿巷道、地铁隧道等地下场景执行任务，具有效率高且不惧危险的优点。然而地下场景存在工况复杂、路面条件恶劣、无 GPS 和通信不畅等因素，对移动机器人定位与建图造成巨大挑战，尤其是地下狭长隧道还存在少特征的退化场景，地面常用定位方法无法直接应用。为解决以上问题，本文采用激光雷达、超宽带、惯性测量单元融合的方案，开展面向地下狭长隧道的移动机器人定位与建图方法研究，主要工作如下：

（1）移动机器人定位与建图平台系统建立。首先构建移动机器人软硬件平台，结合场景特征选取定位与建图所需传感器，然后结合机器人运动状态描述，进一步建立所搭载传感器的观测模型，研究其适用性，为后续算法研究和实验验证提供平台基础。

（2）针对地下狭长隧道环境的激光 SLAM 算法进行对比研究。首先介绍并分析机器人状态估计方法，然后从原理上对比分析三种目前应用最广泛的激光 SLAM 算法，进一步的，通过室内长走廊、长隧道实验研究对三种算法的适应性和可靠性进行了分析，发现现有算法应用于狭长隧道存在局限性，无法很好的应对狭长隧道、颠簸路面导致的传感器退化带来的误差问题。

（3）针对现有定位算法在本文环境存在的问题，提出使用 UWB 定位系统辅助的方法提高定位与建图的精度。基于 UWB 无线定位技术，使用基于 EKF 的方法融合 IMU 观测信息构建 UWB 定位系统，同时设计实验验证其精度和在地下狭长隧道环境中的适用性。实验结果表明所提出的定位系统在狭长隧道中的定位精度均值为 22.3cm。

（4）构建激光-超宽带融合 SLAM 系统。使用基于图优化的框架将 UWB 定位系统提供的位置约束添加到位姿图优化约束中，为扫描匹配提供可靠的初始估计。通过点云去畸变、半径滤波和体素网格滤波等原始点云预处理方法结合优化后的位姿进行精确位姿估计和建图。最后通过真实地下狭长隧道实验证明提出的方案是有效的。

本论文有图 54 幅，表 17 个，引用格式 74 篇。

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图 4-4 视觉捕捉设备及机器人平台

Figure 4-4 Vision capture equipment and robot platform

NOKOV 度量动作捕捉在研究中的应用摘录

> *4.4.1 室内封闭环境实验及分析*
> *移动平台的真实轨迹通过北京 Nokov 公司的动作捕捉系统及分析处理软件给出，配备 Mars 2H 系列动作捕捉镜头的该系统最高可以提供亚毫米级别的定位精度。*

引用格式 赵宇.面向地下狭长隧道的移动机器人定位与建图方法研究[D].中国矿业大学，2021.DOI：10.27623/d.cnki.gzkyu.2021.001210.

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面向上甑工艺的机器人作业系统研究

关键词

自动化酿酒；上甑铺料；机器人轨迹规划；动态时间规整；机器人动力学

摘要

在白酒酿造工厂中，大部分工艺流程通常由人工完成。为了促进白酒酿造行业的工业自动化发展，减轻高重复性的人工劳作，现关注白酒酿造过程中的上甑环节，分析上甑师傅典型作业手法，设计一套面向上甑工艺的机器人作业系统。首先，提出一种基于样条曲线-高斯模型的上甑轨迹泛化编码算法，通过现场采集人工上甑的动作数据，将其导入泛化模型得到人工上甑工艺在空间中的轨迹特征；之后，分析人工上甑工艺特性，划分机器人上甑区域，设计甑料流速可控的末端料斗机构，并结合现场布局对每个区域的铺洒轨迹进行计算；为实现期望厚度的上甑工艺要求，建立机器人动力学逆解模型，根据机器人各关节负载限制得到每个区域的最大速度，结合末端料斗机构的伺服控制性能，制定上甑作业时铺洒厚度的控制策略；最后，通过多次上甑实验，验证了设计的机器人作业系统的有效性。

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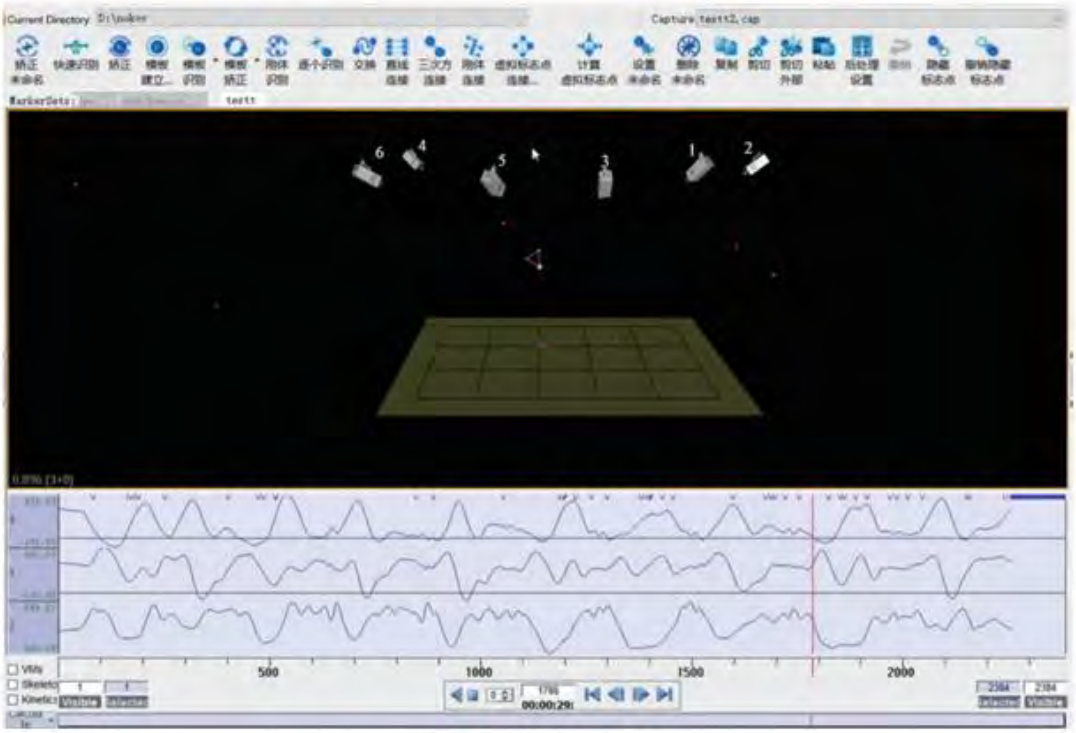

图 2　Nokov 红外动作捕捉系统

Fig. 2　The Nokov infrared motion capture system

NOKOV 度量动作捕捉在研究中的应用摘录

1.　1 基于动态时间规整算法的时间对齐
在人工上甑的过程中(图 1)，将三颗红外反射小球固定在簸箕边缘上，利用如图 2 所示的 Nokov 红外动作捕捉系统采集上甑过程中簸箕的空间运动轨迹。

引用格式　杨艺,王宏彬,张栗寅等.面向上甑工艺的机器人作业系统研究[J].科学技术与工程,2021,21(36):15516-15528.

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人手操作目标物体过程运动轨迹的规律研究

关键词

三指运动步态；手指运动轨迹；运动规律

摘要

根据手指生理学特性及手指间的运动特性，对三指操作单位球体运动过程进行了分析，设计了手指的运动步态模式并讨论了操作过程指尖的运动特点及指尖运动轨迹规律。采用 NOKOV 软件视觉捕捉系统，对手指操作过程的物体转动速度和手指运动轨迹进行了测定，并对三指转动操作运动进行解析模拟和对比。结果表明，人手操作目标物体的手指转动运动符合规划步态的运动规律。研究结果对手指重定位物体的运动仿真和手内操作的步态规划具有指导意义。

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(a) 指尖运动轨迹实验　　(b) 食指关节角度测量实验

图 6　三指操作目标物体实验

NOKOV 度量动作捕捉在研究中的应用摘录

操作过程的数据测量模拟用三指按照所规划的步态操作直径为 40mm 的乒乓球，对这一过程用 NOKOV 光学三维动作捕捉系统的摄像功能对手指操作目标物体的过程进行摄像。　nokov 系统可采集人手的操作过程的运动轨迹和运动学参数，并进行数据处理。

引用格式 张亚琪,周邦达,马小龙等.人手操作目标物体过程运动轨迹的规律研究[J].高技术通讯,2021,31(04):417-424.

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https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C44YLTlOAiTRKibYIV5Vjs7iy_Rpms2pqwbFRRUtoUImHYYkLGskLxp7Uteqa5drUS12T3Zw6X0dayQTSQvlkoGK&uniplatform=NZKPT

无线传感器网络分布式安全定位问题研究

关键词

无线传感器网络；安全定位；欺骗攻击；拒绝服务攻击；隐私保护

摘要

随着传感技术、无线通讯技术与嵌人式计算的不断进步以及数字电路、微机电系统的蓬勃发展，无线传感器网络（Wireless Sensor Network，WSN）作为一种集数据采集、存储、传输与控制处理于一体的分布式信息系统，能够实时感知和监测部署区域内环境或目标的数据信息。定位作为无线传感器网络的一项关键技术，通过提供位置信息，可实现空间感知、目标跟踪、环境监测和紧急救援等多种功能。高精度定位能够增强网络效能，提高数据关联和决策支持的有效性，因而对于无线传感器网络的实际应用至关重要。然而，由于无线通信的开放性、部署环境的不确定性以及有限资源的约束性等原因，无线传感器网络极易遭受各类安全威胁，从而引起定位失准，进而降低系统性能，甚至导致系统崩溃。因此，近年来无线传感器网络的安全定位问题逐渐受到研究学者的关注，相关研究已在无线通信、网络安全以及协调控制等多个领域取得了丰硕成果，但仍存在一些不足。首先，现有的安全定位研究大多基于无需测距的定位方法，同时由于受到环境变化、信号传播损耗等因素的不利影响，其定位精度不高，有必要探索基于测距技术的安全定位方案。其次，现有大多数安全定位算法通常针对某种特定形式的攻击设计，这限制了它们抵御不同攻击的适用性，迫切需要建立一种通用攻击模型，以设计更具鲁棒性的安全定位算法。然后，当前安全定位研究主要关注节点遭受恶意攻击的情形，却忽略了针对无线通信链路的潜在威胁，需要考虑通信链路安全性，为制定更具普适性的安全定位方法提供有力指导。再者，忽视节点位置隐私保护可能带来严重的安全威胁，而传统的加密和鉴权机制往往会带来较大的计算开销，研究如何在保护位置隐私的同时，高效实现无线传感器网络定位是一个亟待解决的科学问题。

鉴于上述研究现状中存在的问题，结合当前新一代传感器技术发展的实际情况，本文旨在从数据完整性、数据可用性、链路有效性以及数据机密性四个方面，研究无线传感器网络的分布式安全定位问题，具体研究内容概括如下：

1．针对现有基于测距的定位方法难以抵御威胁性较大的欺骗攻击这一问题，基于无线传感器网络定位原理及典型安全威胁模型，首先建立了基于接收信号强度指标（Received Signal Strength Indicator，RSSI）测距值欺骗的三种具体攻击形式的数学模型。其次，针对瞬时破坏力最大化的浪涌注人攻击，基于RSSI测距值的统计特征，提出了一种针对三角测量集的可信度评估方案，并结合均值滤波与数据融合技术，设计了一种基于信任评估策略的分布式定位算法。再者，针对持续累积的偏差注人攻击，提出了一种固定时间间隔检测方案，然后基于异常检测结果，结合数值拟合方法，设计了一种基于偏差修正的分

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布式定位算法。数值仿真结果表明，上述算法均可以在测距值被欺骗攻击篡改的情况下实现精确定位。

2．针对当前研究防御攻击类型单一这一问题，结合拒绝服务攻击的特点与网络应用的实际情况，建立了一种包含攻击活跃期与休眠期的通用周期性拒绝服务攻击模型，该模型不需要对攻击内在策略作出任何假设，攻击者的行为仅由攻击的持续时间和攻击发起频率决定，可在效率与资源之间进行灵活权衡。然后，基于重心坐标表示的分布式迭代定位框架，提出了一种基于保持策略的更新规则，它允许传感器在遭受攻击时利用在上一个攻击休眠期的最后一个时刻从其邻居收集的数据包更新其坐标。此外，还从理论上证明了该算法在不考虑具体攻击策略的情况下能够收敛到传感器的准确位置。最后，在树莓派平台上进行了实验，其结果与理论结论一致。

3．针对现有研究大多忽略了通信链路安全这一问题，首先利用伯努利随机变量对传感器节点从控制器到执行器的无线通信链路有效性进行表征，建立了一种更为泛化的随机损耗链路模型。其次，通过测量无线传感器网络中节点对之间的距离确定重心坐标，以此作为基于测距的定位方案，并在此基础上提出了一种更具普适性的分布式迭代定位算法。然后，利用次随机矩阵乘积的收敛性，从理论上证明了该算法的全局收敛性，算法复杂度分析结果显示该算法的计算量与通信开销均较低。最后，通过数值算例验证了该算法在网络存在随机损耗链路的情形下可以实现精确定位。

4．针对当前研究中隐私保护与资源约束存在矛盾这一问题，首先结合实际工作场景中网络通信通常具有时变时滞的情形，在对比分析加密机制、状态分解以及差分隐私等隐私保护方法的基础上，建立了分布式隐私保护定位问题的理论模型。其次，为了实现对节点位置信息的隐私保护，提出了一种基于异步迭代与噪声注入双重保护策略的分布式定位算法，其中，异步迭代策略在避免隐私泄露的同时，还减少了通信开销，降低了网络拥塞的风险；而设计的注入噪声能够在定位过程中完全抵消，从而不会降低系统定位性能。再者，从算法收敛性、复杂度以及安全效能三个方面验证了所提出的分布式隐私保护定位算法的有效性。最后，通过无人车组网实验，进一步验证了该算法能够在保护节点位置信息隐私的前提下，实现精确定位。

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图 6-1 无人车实验平台

NOKOV 度量动作捕捉在研究中的应用摘录

9 个无人车被部署在一个 10×10 m²的正方形区域，该区域由 24 个 Mars4H 相机镜头组成的 NOKOV 光学三维运动捕捉系统覆盖，该运动捕捉系统可以提供亚毫米级别的位置数据。图 6 - 2 为ＮＯＫＯＶ运动捕捉系统的软件界面显示，从中可以看到运动捕捉系统的覆盖范围与无人车的部署位置。

引用格式 王雅.无线传感器网络分布式安全定位问题研究[D].电子科技大学，2023.DOI：10.27005/d.cnki.gdzku.2023.005916.

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https://kns.cnki.net/kcms2/article/abstract?v=DFdco8SIy0LvmnK8MaFHNKNR-lgezMazkDIsipq9gFqyJ7OPUp4LxhTRqP-U-Q7J-d62LRyjTfwBp_ZOHrjyB5kx272s1zy4nzDf7J0LZBELgVDyi9IFtQ==&uniplatform=NZKPT&language=gb

基于特征锚点跟踪的小行星着陆导航方法研究

关键词

高精度自主导航；实时位姿估计；特征锚点跟踪；目标检测；

摘要

针对小行星探测器在下降着陆段对高精度实时自主导航的任务需求，综合考虑星载计算资源受限与小行星复杂地表环境因素等，提出了一种基于特征锚点跟踪的小行星着陆自主导航方法。利用 3DSIFT 算法从小行星三维点云数据中提取初始特征点，并通过空间分布特征筛选机制选取具有高辨识度的特征锚点，为后续视觉跟踪提供精确的三维定位参考基准；采用轻量级卷积神经网络直接检测并跟踪特征锚点在图像序列中的二维投影，避免了传统方法中计算密集的特征匹配步骤，在保证导航精度的同时显著降低了计算复杂度；基于建立的 2D-3D 点对应关系，基于 EPnP 方法实现探测器位姿参数的精准估计。通过软件仿真和半物理试验验证，该方法在保证位姿估计精度的同时，可有效降低导航系统的计算负荷，为小行星探测下降着陆段的自主导航提供了一种高效可靠的解决方案。

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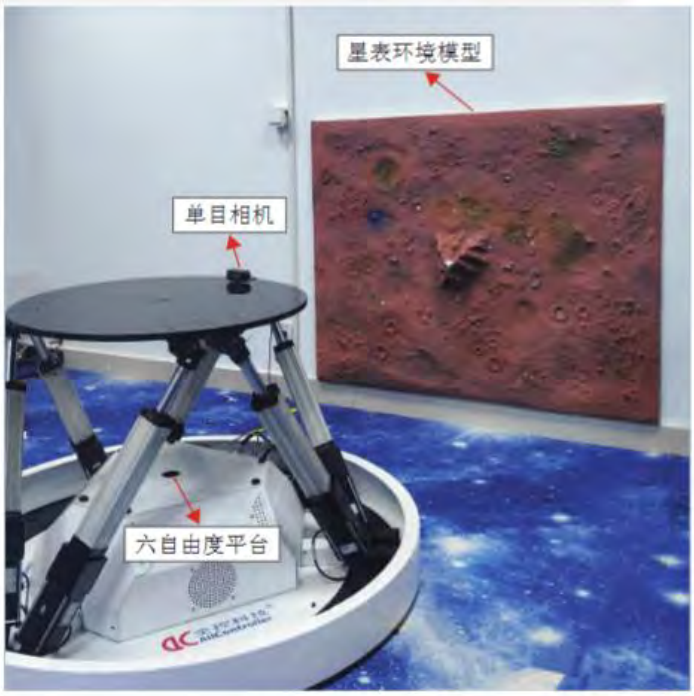

图 9　半物理仿真测试平台

Fig. 9　Hardware-in-the-loop simulation test platform

NOKOV 度量动作捕捉在研究中的应用摘录

3.2 位姿精度评估半物理试验验证

针对试验条件限制以及精度验证需求，本研究选择在具有高精度六自由度平台系统的室内搭建半物理试验场景，通过星表环境模型模拟小行星地表特征，并将单目相机搭载于六自由度平台上实现探测器下降过程动态模拟。其中，采用的星表环境模型基于小行星形貌特征构建，完整复现了典型小行星表面特征，包括多尺度陨石坑、不规则岩石块及风化层等关键地形要素，可准确模拟真实小行星的地表特征。此外，使用 Zivid 2 + 3D 相机对星表环境模型完成三维点云采集，并在室内场景中部署 Nokov 光学三维运动捕捉系统进行坐标系之间的转换。试验用到的六自由度平台及星表环境模型等设备如图 9 和图 10 所示。

引用格式 吴佳琦,余萌,韩亮亮,等.基于特征锚点跟踪的小行星着陆导航方法研究[J].深空探测学报(中英文),2026,13(01):38-49.

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Part II Life Sciences

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A Binocular-Camera-Assisted Sensor-to-Segment Alignment Method for Inertial Sensor-Based Human Gait Analysis

Keywords

Binocular camera, inertial measurement unit, joint angle estimation, Open Pose, sensor-to-segment alignment.

Abstract

Lower limb joint angles are powerful clinical indicators for mobility assessment and gait rehabilitation training. Inertial motion capture (IMC), which is both accurate and convenient, is becoming an ideal method to estimate joint angles. Considering that the corresponding segment and sensor frame are usually misaligned, an alignment procedure is required to determine the orientation offset between the segment and the sensor frame. This article presents a binocular-camera-assisted alignment procedure to align the frames of segment and inertial sensor. This procedure uses a binocular camera to acquire lower limb segment's initial orientations with image-based human pose algorithm and then estimates the joint angle with kinematic constraint. The alignment procedure requires only sitting posture and does not need any functional movement. Ten healthy participants were recruited for the validation experiments, which included stand-up, turn-around, and walking. The accuracy and effectiveness of our alignment procedure were validated against the optical motion capture (OMC). The mean root mean square errors (RMSEs) of hip, knee, and ankle angles were 1.6◦,2.9◦,and3.9◦, respectively.The result demonstrates that our procedure performs well on joint angle estimation.The proposed alignment procedure did not require any complicated functional movement, but only sitting posture, which could enable more practical joint angle estimation for patient subjects in clinical applications.

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Fig. 5. Inertial sensors and OMC markers on human lower limb.

How NOKOV Contributes to the Research

An OMC system (Mars, Nokov3DOMCP, Beijing, China) with eight infrared cameras was used as the "Gold Standard" for validation experiments.

Citation S. Cai, M. Shao, M. Du, G. Bao and B. Fan, "A Binocular-Camera-Assisted Sensor-to-Segment Alignment Method for Inertial Sensor-Based Human Gait Analysis," in IEEE Sensors Journal, vol. 23, no. 3, pp. 2663-2671, 1 Feb.1, 2023, doi: 10.1109/JSEN.2022.3229384.

Link https://ieeexplore.ieee.org/document/9994701

A forward-inverse dynamics modeling framework for human musculoskeletal multibody system

Keywords

Multibody dynamics, Musculoskeletal modeling, Gait, Forward-inverse dynamics, Musculotendon dynamics

Abstract

Multibody musculoskeletal modeling of human gait has been proved helpful in investigating the pathology of musculoskeletal disorders. However, conventional inverse dynamics methods rely on external force sensors and cannot capture the nonlinear muscle behaviors. Meanwhile, the forward dynamics approach is computationally demanding and only suited for relatively simple tasks. This study proposed an integrated simulation methodology to fulfill the requirements of estimating foot-ground reaction force, tendon elasticity, and muscle recruitment optimization. A hybrid motion capture system, which combines the marker-based infrared device and markerless tracking through deep convolutional neural networks, was developed to track lower limb movements. The foot-ground reaction forces were determined by a contact model for soft materials, and its parameters were estimated using a two-step optimization method. The muscle recruitment problem was first resolved via a static optimization algorithm, and the obtained muscle activations were used as initial values for further simulation. A torque tracking procedure was then performed by minimizing the errors of joint torques calculated by musculotendon equilibrium equations and inverse dynamics. The proposed approach was validated against the electromyography measurements of a healthy subject during gait. The simulation framework provides a robust way of predicting joint torques, musculotendon forces, and muscle activations, which can be beneficial for understanding the biomechanics of normal and pathological gait.

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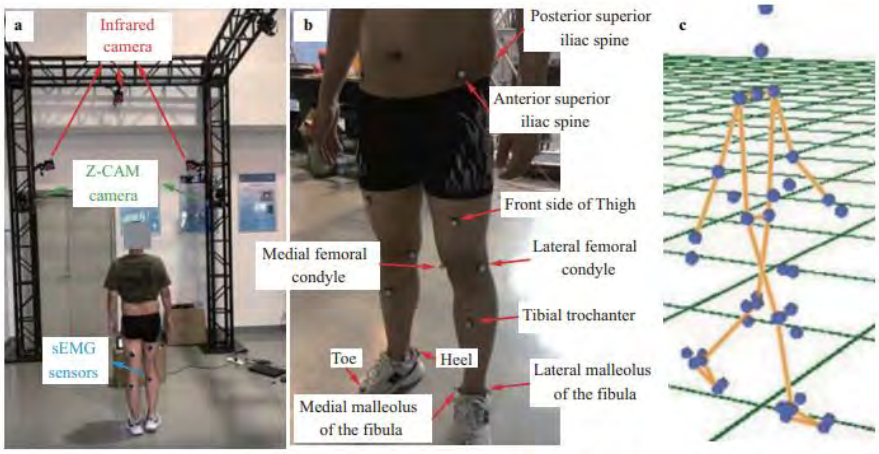

Figure 1 Experimental setup and procedure. **a** Infrared-AI hybrid motion capture system; **b** modified Helen Haynes marker arrangement; **c** landmark positions obtained via hybrid motion capture system.

How NOKOV Contributes to the Research

As shown in Fig. 1a, motion data were collected synchronously using an eight-lens infrared motion tracking system (Nokov Tech., Beijing, China) and four Z-CAM cameras (ImagineVision Tech., Shenzhen, China) at a sample rate of 60 Hz. Both camera systems were calibrated simultaneously based on an L-frame calibration object.

Citation Wang X, Guo J, Tian Q. A forward-inverse dynamics modeling framework for human musculoskeletal multibody system[J]. Acta Mechanica Sinica, 2022, 38(11): 522140.

Link https://link.springer.com/article/10.1007/s10409-022-22140-x

A General Framework of Knowledge-Based Coaching System with Application in Table Tennis Training

Keywords

Knowledge-based coaching system; Sequential decision problem; Table tennis training; Motion capture

Abstract

As the growth of people's awareness in health and fitness, high-level sports exercise coaching resources become scarce comparing to the fast increasing demands. In traditional sports training, coaches are responsible for scheduling training sessions and giving instructions based on the performance of the trainee. This paper proposes a general knowledge-based coaching system (KBCS) for the purpose of automatic and intelligent sports training. Through systematically modeling the interactive training process between the coach and the trainee as a sequential decision problem, we show that the knowledge-based training controller can be properly designed to help the trainee to make effective progress towards the preset training goal. Partial implementation of KBCS in the table tennis training has been realized to demonstrate and verify the effectiveness of the proposed method.

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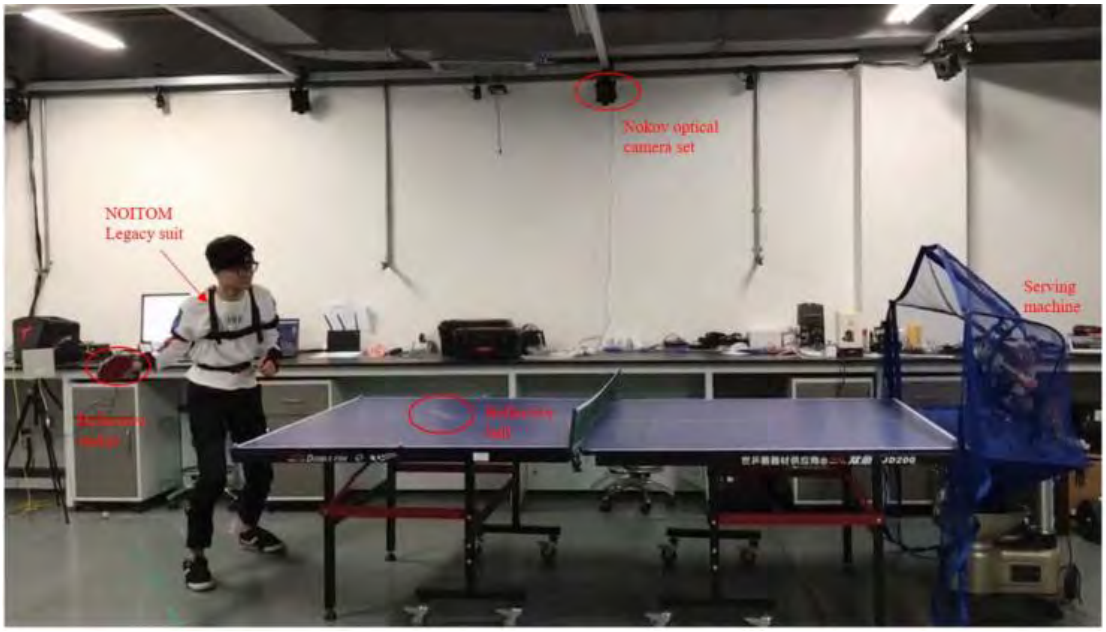

How NOKOV Contributes to the Research

According to the above design, an experimental platform is built as shown in Fig. 5. A NOKOV Motion Capture System was used to capture the trajectory of balls and the racket. The table tennis balls are covered with reflective material and the racket is attached reflective markers around the edge for better results. Besides, a NOITOM Perception Legacy suit is worn by the trainee for accurate posture recording. Four students are recruited and their data are analyzed.

Citation Yan W, Ma H, Yang Z. A general framework of knowledge-based coaching system with application in table tennis training[C]//2020 39th Chinese control conference (CCC). IEEE, 2020: 2902-2907.

Link https://ieeexplore.ieee.org/abstract/document/9188412

A Human-Prosthesis Coupled Musculoskeletal Model for Transtibial Amputees

Keywords

Musculoskeletal model, Transtibial amputees, Muscle forces, Robotic prosthesis

Abstract

In this paper, we present a human-prosthesis coupled full-body musculoskeletal model that integrates the dynamics of the muscle-driven human body and a motor-driven robotic prosthesis. This model can be used to perform the inverse kinematics and dynamics calculation based on measurements for amputees wearing a force-controlled or position-controlled prosthesis. As a result, we can analyze the impacts of prostheses on amputee kinetic states, such as joint torques and muscle forces. To verify the proposed model, we conducted experiments involving four transtibial amputees wearing passive prostheses and our self-developed robotic prostheses. We estimated the joint angles, joint torques, and muscle forces on the intact side and on the residual side of the subjects. The indexes reflecting the symmetry and magnitude of muscle forces were introduced to evaluate the effects of different prostheses on transtibial amputees. The indexes of muscle force magnitude indicate that the posterior thigh muscles of the residual limb exhibit significant compensation during walking. And the indexes of muscle force symmetry indicate that active prostheses with higher damping rates work better for fast walking speeds, while those with lower damping rates are more suitable for slow walking speeds. The proposed approach may offer a novel method for evaluating prostheses that considers muscle-level kinetics, thus enhancing understanding of the impact of different prostheses on the movements of amputees.

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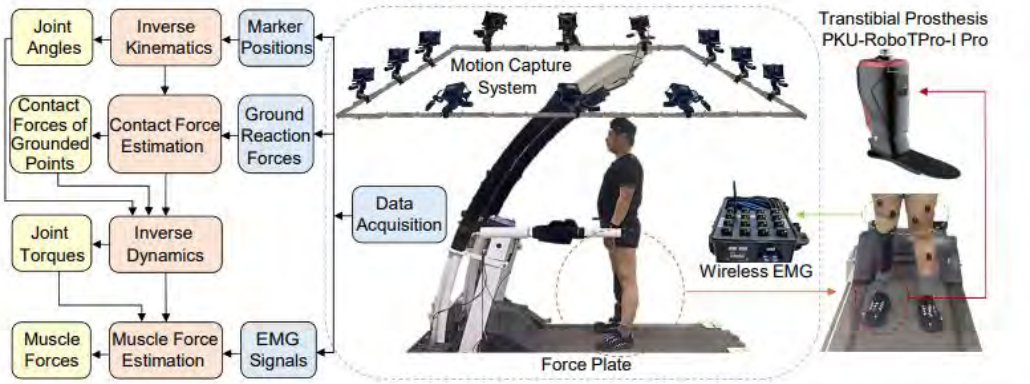

Fig. 1. Calculation flow in sDIMS based on the embedded musculoskeletal model, including data acquisition from the experimental platform.

How NOKOV Contributes to the Research

The experimental platform is depicted in Fig.1 along with the calculation flow. The motion data were captured by an optical motion capture system comprising 12 cameras (MARS4H, NOKOV, China), while EMG signals were recorded using awireless EMG system (Delsys Trigno Wireless EMG System,Delsys, USA) with 16 channels. Ground contact forces were measured using a treadmill with one force plate (Gaitway-3D 150/50, H/P/COSMOS, Germany).

Citation Lu Y, Huang Y, Yang R, et al. A Human-Prosthesis Coupled Musculoskeletal Model for Transtibial Amputees[J]. IEEE Transactions on Biomedical Engineering, 2025.

Link https://ieeexplore.ieee.org/abstract/document/10845183

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A markless 3D human motion data acquisition method based on the binocular stereo vision and lightweight open pose algorithm

Abstract

This study aimed to achieve precise 3D human motion data acquisition without the need for markers. Specifically, the proposed system utilized two affordable cameras to capture human motion from diverse angles. It developed a lightweight Open Pose algorithm to extract 2D human body joints from recorded videos. Subsequently, a stereo-matching method was applied to derive accurate 3D human body joint data. Comprehensive experiments with 10 healthy participants showcased the system's exceptional performance, demonstrating superior measurement accuracy compared to established standards like the NOKOV system (RMSE values consistently below 9°) and commonly used Microsoft Kinect devices (V2 and Azure). This innovative binocular vision system presents a new approach to motion capture, potentially offering a cost-effective and precise tool for practical applications across various scenarios (e.g., motor functional assessment, virtual avatar streaming), contributing significantly to both scientific and academic communities.

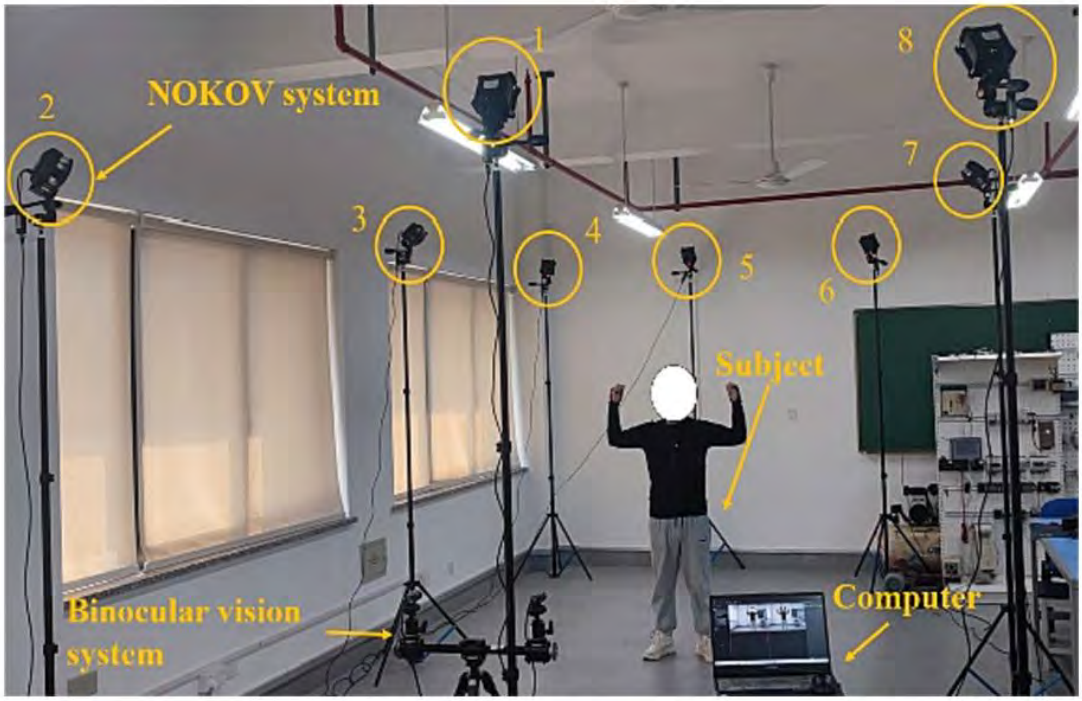

Fig. 20. Experimental setup: the proposed binocular vision system and the NOKOV system.

How NOKOV Contributes to the Research

In the experiments, this research compared the human motion data obtained by the proposed binocular vision system at different distances with data from the gold standard NOKOV and commercially available devices, Kinect and Azure Kinect, both of which do not require markers. This comparison aimed to validate the reliability, effectiveness, and consistency of the proposed binocular vision system.

Citation Bo Sheng, Linfeng Chen, Jian Cheng, Yanxin Zhang, Zikai Hua, Jing Tao,A markless 3D human motion data acquisition method based on the binocular stereo vision and lightweight open pose algorithm, Measurement,Volume 225,2024,113908,ISSN 0263-2241,https://doi.org/10.1016/j.measurement.2023.113908.

Link https://www.sciencedirect.com/science/article/abs/pii/S0263224123014720

A Multi-sensor Gait Dataset Collected Under Non-standardized Dual-Task Conditions

Abstract

Non-standardized dual-tasks have recently gained attention in gait analysis. Currently, there is a lack of publicly available non-standardized dual-task gait datasets collected with multiple sensors. To fill this gap, we present a dataset (NONSD-Gait) consisting of back and forth 7 m walks under three non-standardized dual-task conditions (texting, browsing the web, and holding a cup) from 23 healthy adults. These data were collected simultaneously by three common types of sensors: an optical motion capture (MOCAP) system, a depth camera and an inertial measurement unit (IMU). MOCAP captured the 3D trajectories of 22 markers using 8 optical cameras, while the depth camera recorded the 3D trajectories of 25 joints. The IMU was placed on the left ankle to record acceleration and angular velocity data. Moreover, we extracted 10 spatio-temporal gait parameters and 168 kinematic parameters. This dataset enables gait analysis under non-standardized dual-task conditions, supporting research on rehabilitation training for cognitive and motor impairments. Additionally, it facilitates cross-device comparisons, facilitating the exploration of low-cost sensor alternatives.

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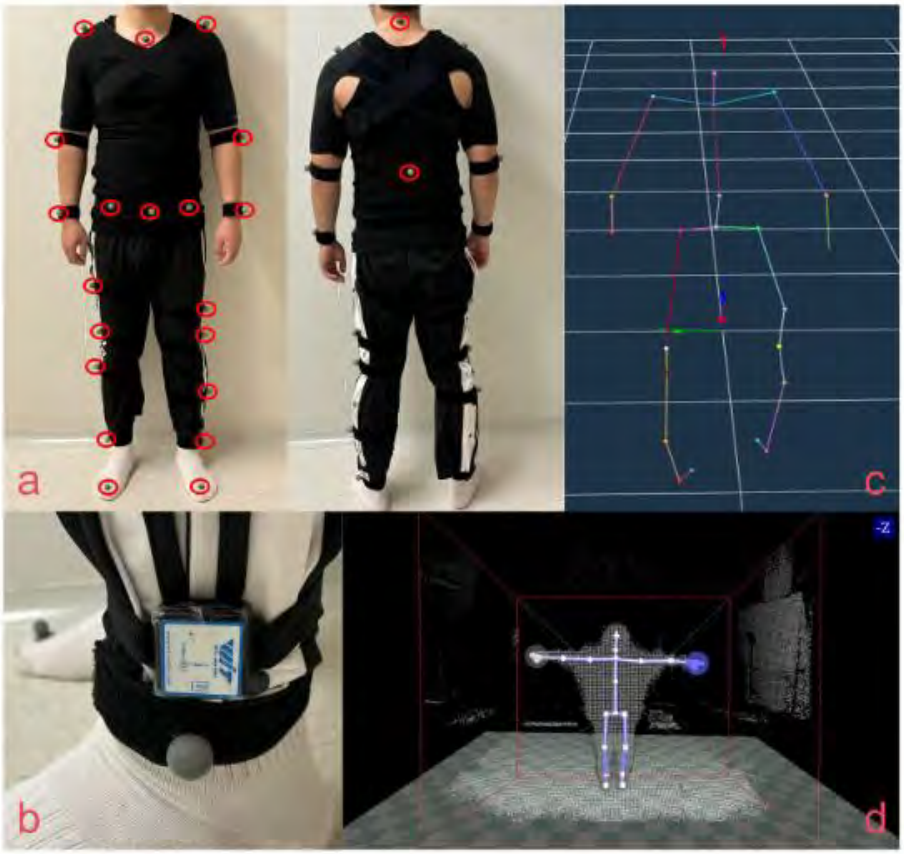

Fig. 3 The display of marker points and the placement of IMU. (a) Placement of markers on the body. (b) Placement of the IMU on the body. (c) Display of marker points in the XINGYING software. (d) Display of marker points in the Kinect's software.

How NOKOV Contributes to the Research

Experimental design. Participants underwent a gait experiment at the laboratory of Intelligent Sensing and Active Health Platform of Sun Yat-Sen University. The space of the laboratory measures 14.2 m × 7 m. In the experi-ment, participants were required to walk back and forth on a 7 m × 1 m mat under a single-task condition and three non-standardized dual-task conditions. The experimental setup is illustrated in Fig. 2. This study utilized eight MOCAP cameras (NOKOV MARS 2H HD cameras, 100 Hz, resolution 2048 × 1088), one depth camera (Microsoft Kinect V2.0, 30 Hz, resolution 512 × 424), and one inertial sensor (Witmotion WT901BLECL5.0, 100 Hz) for data collection.

Citation Liao Y, Cao J, Yu L, et al. A Multi-sensor Gait Dataset Collected Under Non-standardized Dual-Task Conditions[J]. Scientific data, 2025, 12(1): 1121.

Link https://www.nature.com/articles/s41597-025-05458-y

A non-contact system for intraoperative quantitative assessment of bradykinesia in deep brain stimulation surgery

Keywords

Deep brain stimulation; Intraoperative test; Quantitative assessment; Non-contact measurement; Bradykinesia

Abstract

Background and Objective: Deep brain stimulation (DBS) is an effective treatment for a number of neurological diseases, especially for the advanced stage of Parkinson's disease (PD). Objective assessment of patients' motor symptoms is crucial for accurate electrode targeting and treatment. Existing approaches suffer from subjective variability or interference with voluntary motion. This work is aimed to establish an objective assessment system to quantify bradykinesia in DBS surgery. Methods: Based on the analysis of the requirements for intraoperative assessment, we developed a system with non-contact measurement, online movement feature extraction, and interactive data analysis and visualization. An optical sensor, Leap Motion Controller (LMC), was taken to detect hand movement in three clinical tasks. A graphic user interface was designed to process, compare and visualize the collected data and assessment results online. Quantified movement features include amplitude, frequency, velocity, their decrement and variability, etc. Technical validation of the system was performed with a motion capture system (Mocap), with respect to data-level and feature-level accuracy and reliability. Clinical validation was conducted with 20 PD patients for intraoperative assessments in DBS surgery. Treatment responses with respect to the bradykinesia movement features were analyzed. Single case analysis and group statistical analysis were performed to examine the differences between preoperative and intraoperative performance, and the correlation between the clinical ratings and the quantified assessment was analyzed. Results: For the movements measured by LMC and Mocap, the average Pearson's correlation coefficient was 0.986, and the mean amplitude difference was 2.11 mm. No significant difference was found for all movement features quantified by LMC and Mocap. For the clinical tests, key movement features showed significant differences between the preoperative baseline and intraoperative performance when the brain stimulation was ON. The assessment results were significantly correlated with the MDS-UPDRS clinical ratings.

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Conclusions: The proposed non-contact system has established itself as an objective intraoperative assessment, analysis, and visualization tool for DBS treatment of Parkinson's disease.

Fig. 4. Technical validation with a motion capture system.

How NOKOV Contributes to the Research

Experiments were conducted in a laboratory environment equipped with a Mocap system (NOKOV, Beijing Nokov Science and Technology Co., Ltd, China). The Mocap system has eight cameras to detect the markers from different views. Subjects were asked to lie on a ward bed to complete the task, which was consistent with the intraoperative assessment.

Citation Yu N, Yu Y, Lin J, et al. A non-contact system for intraoperative quantitative assessment of bradykinesia in deep brain stimulation surgery[J]. Computer Methods and Programs in Biomedicine, 2022, 225: 107005.

Link https://www.sciencedirect.com/science/article/pii/S016926072200387X

A pilot study on an infrared jaw-tracking method for mandibular motion based on modified bite-fork registration: Accuracy and feasibility

Keywords

Mandibular motion, Infrared tracking, Bite-fork registration

Abstract

Objectives: This study developed a novel method for repeated tracking without requiring secondary cone-beam computed tomography (CBCT) exposure or additional registration operations. Methods: An infrared jaw-tracking method based on the registration of a modified bite-fork was developed. The accuracy of the method was evaluated by comparing head-simulator linear distance measurements obtained using the jaw-tracking and CBCT imaging methods and calculating the root mean square (RMS) errors associated with linear distance deviations. Feasibility was evaluated by analysing the opening–closing motion of the incisor in 15 participants, tracked by 15 dentists, and collecting ratings from both of them. Results: Linear distance measurements showed no significant differences between the jaw-tracking and CBCT imaging methods at each position (all $P > 0.05$). The overall RMS errors of the jaw-tracking method were within 0.35 mm. Mean length of the opening curvilinear path (50.80 ± 6.86 mm) was not significantly different from the reported value ($P = 0.684$), and the intraclass correlation coefficient for the opening curvilinear path length was 0.947 ($P < 0.001$). A 'figure-eight' pattern of the opening–closing trajectory was observed. The mean rating score for each item was ≥ 4.0. Conclusions: This jaw-tracking method based on modified bite-fork registration enables repeated tracking without requiring secondary CBCT radiation exposure or additional registration operations. Clinical significance: The infrared jaw-tracking method offers a promising approach for short-term repeated evaluation of mandibular motion due to its low radiation exposure and minimal chair-site costs.

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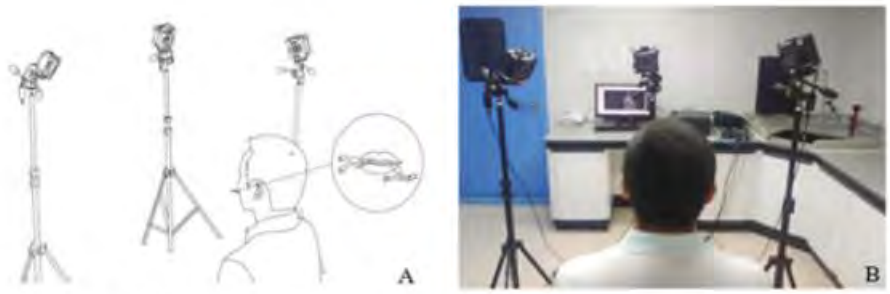

Fig. 3. Infrared cameras. A: placement diagram for the infrared cameras; B: mandibular motion tracking using three infrared cameras.

How NOKOV Contributes to the Research

Modified bite-fork, personalised trackers, and NOKOV infrared cameras (Beijing Nokov Science & Technology Co., Ltd., Beijing, China) were used for jaw-tracking. The modified bite-fork (Fig. 1) and maxillary and mandibular trackers (Fig. 2) were designed using Exocad software (exocad GmbH, Darmstadt, Germany) and Geomagic Wrap (3D Systems Inc., Rock Hill, SC, USA), based on the participants' intraoral scan models. These components were fabricated using a biocompatible resin and a 3D printer (Objet350 Printer, Stratasys Ltd., Eden Prairie, MN, USA).

Citation Du B, Wang X, Jiang H, et al. A pilot study on an infrared jaw-tracking method for mandibular motion based on modified bite-fork registration: Accuracy and feasibility[J]. Journal of Dentistry, 2025, 159: 105766.

Link https://www.sciencedirect.com/science/article/abs/pii/S0300571225002106

A Wearable Biofeedback Device for Monitoring Tibial Load During Partial Weight-Bearing Walking

Keywords

Tibial force, rehabilitation, partial weight-bearing, machine learning, ambulatory monitoring

Abstract

Patients with tibial fractures are usually advised to follow a partial weight-bearing gait rehabilitation program after surgery to promote bone healing and lower limb functional recovery. Currently, the biofeedback devices used for gait rehabilitation training in fracture patients use ground reaction force (GRF) as the indicator of tibial load. However, an increasing body of research has shown that monitoring GRF alone cannot objectively reflect the load on the lower limb bones during human movement. In this study, a novel biofeedback system was developed utilizing inertial measurement units and custom instrumented insoles. Based on the data collected from experiments, a hybrid approach combining a physics-based model and neural network architectures was used to predict tibial force. Compared to the traditional physics-based algorithm, the physical guided neural networks method showed better predictive performance. The study also found that regardless of the type of weight-bearing walking, the peak tibial force was significantly higher than the peak tibial GRF, and the time at which the peak tibial compression force occurs may not be consistent with the time at which the peak vertical GRF occurs. This further supports the idea that during gait rehabilitation training for patients with tibial fractures, monitoring and providing feedback on the actual tibial force rather than just the GRF is necessary. The developed device is a non-invasive and reliable portable device that can provide audio feedback, providing a viable solution for gait rehabilitation training outside laboratory and helping to optimize patients' rehabilitation treatment strategies.

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How NOKOV Contributes to the Research

On the day of data collection, 26 retro-reflective markers were placed on each subject's body. During walking, the marker trajectories were recorded with 8-camera motion capture system (Nokov, Beijing, China) at 200 Hz, and two force plates (Bertec, Ohio, USA) embedded in the walkway were used to collect 3D GRF during walking.

Citation Ma T, Xu X, Chai Z, et al. A wearable biofeedback device for monitoring tibial load during partial weight-bearing walking[J]. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2023, 31: 3428-3436.

Link https://ieeexplore.ieee.org/abstract/document/10217015

Analysis of ergonomic load and fatigue in live-line work based on surface electromyography and motion capture

Keywords

surface electromyography(sEMG), live-line work, ergonomic, fa-tigue, motion capture, work posture

Abstract

Explore the adverse ergonomic factors that induce fatigue and musculoskeletal disease during live-line operation. Recruitment 10 male volunteers to participate in the simulation of the installation and removal of insulating protective cover. Measuring height, weight and maximum voluntary contraction (MVC) before the task. During the simulation, collecting the participants' subjective fatigue scores, motion captured data and the sEMG of deltoid, biceps, triceps and brachioradialis. Conducting Jointed EMG Amplitude and Spectrum Analysis (JASA) based on the root mean square (RMS) and median frequency (MF). The differences in the right elbow flexion, right elbow pronation, left elbow flexion, left shoulder extension rotation, and left shoulder abduction at different times of task were statistically significant (\\(P < 0.05\\)). Kinematic analysis revealed significant alterations in upper-limb joint motion patterns, which correlated with the progression of muscular fatigue. The left deltoid, right biceps brachii, right triceps brachii, left brachioradialis, and right brachioradialis are the five primary muscle groups involved in work processes and are prone to fatigue. The repetition times of the operation are the adverse ergonomics factor which influenced the live-line workers fatigue condition. A reasonable labor organization should be formulated. Health promotion and education should be conducted to correct poor work postures. In addition, the development of supported equipment can be carried out based on the range of motion of the elbow and shoulder joints during the operation.

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Figure 4: ***Example of the installation and removal of insulating protective cover***

How NOKOV Contributes to the Research

Using the NOKOV optical 3D motion capture system to acquire and process kinematic data. The 25 markers upper limb model allowed recording of shoulder and elbow joint movements. Reflective markers attached to the participants were captured by cameras, enabling visualization of joint trajectories during the tasks. An example of marker placement is shown in Figure 3.

Citation Chen, Chu & Liu, Conghan & Lu, Xin & Pan, Ruijian & Li, Min & Liu, Lei. (2025). Analysis of ergonomic load and fatigue in live-line work based on surface electromyography and motion capture. 1005-1011. 10.1145/3772726.3772884.

Link https://dl.acm.org/doi/10.1145/3772726.3772884

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Comparison of kinematics and joint moments calculations for lower limbs during gait using markerless and marker-based motion capture

Keywords

3D motion analysis, deep learning, artificail intelligence, joint moment, markerless motion capture

Abstract

Lower limb joint angles are powerful clinical indicators for mobility assessment and gait rehabilitation training. Inertial motion capture (IMC), which is both accurate and convenient, is becoming an ideal method to estimate joint angles. Considering that the corresponding segment and sensor frame are usually misaligned, an alignment procedure is required to determine the orientation offset between the segment and the sensor frame. This article presents a binocular-camera-assisted alignment procedure to align the frames of segment and inertial sensor. This procedure uses a binocular camera to acquire lower limb segment's initial orientations with image-based human pose algorithm and then estimates the joint angle with kinematic constraint. The alignment procedure requires only sitting posture and does not need any functional movement. Ten healthy participants were recruited for the validation experiments, which included stand-up, turn-around, and walking. The accuracy and effectiveness of our alignment procedure were validated against the optical motion capture (OMC). The mean root mean square errors (RMSEs) of hip, knee, and ankle angles were 1.6◦,2.9◦,and3.9◦, respectively.The result demonstrates that our procedure performs well on joint angle estimation.The proposed alignment procedure did not require any complicated functional movement, but only sitting posture, which could enable more practical joint angle estimation for patient subjects in clinical applications.

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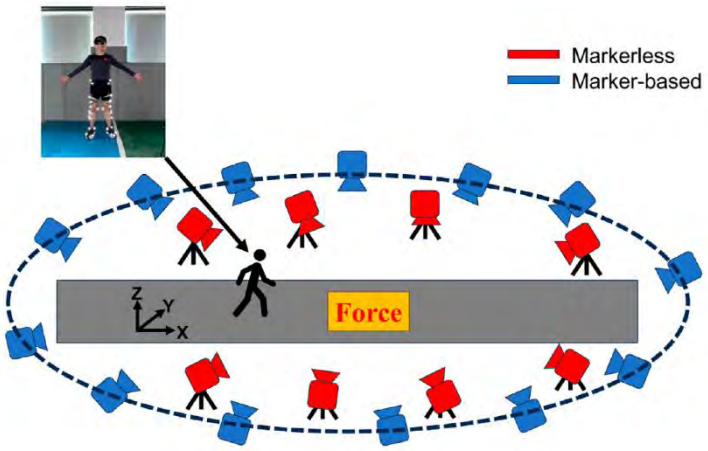

FIGURE 2
Overhead view experimental setup and markers' locations on the body.

How NOKOV Contributes to the Research

An MB motion capture system (thirteen Mars 4H (Nokov Motion Capture System, Beijing, China), 4.1-megapixel resolution cameras) and an MMC system (eight Z-CAM-E2 (Intetech, Beijing, China), 120HZ, 8-megapixel resolution) were used to capture the movement synchronously.

Citation Huang T, Ruan M, Huang S, et al. Comparison of kinematics and joint moments calculations for lower limbs during gait using markerless and marker-based motion capture[J]. Frontiers in Bioengineering and Biotechnology, 2024, 12: 1280363.

Link https://www.frontiersin.org/articles/10.3389/fbioe.2024.1280363/full

Construction of a niche-specific spinal white matter-like tissue to promote directional axon regeneration and myelination for rat spinal cord injury repair

Keywords

Extracellular matrix; Oligodendroglial lineage cells; White matter-like tissue; Directional axon regeneration; Spinal cord injury

Abstract

Directional axon regeneration and remyelination are crucial for repair of spinal cord injury (SCI), but existing treatments do not effectively promote those processes. Here, we propose a strategy for construction of niche-specific spinal white matter-like tissue (WMLT) using decellularized optic nerve (DON) loaded with neurotrophin-3 (NT-3)-overexpressing oligodendrocyte precursor cells. A rat model with a white matter defect in the dorsal spinal cord of the T10 segment was used. The WMLT transplantation group showed significant improvement in coordinated motor functions compared with the control groups. WMLT transplants integrated well with host spinal cord white matter, effectively addressing several barriers to directional axonal regeneration and myelination during SCI repair. In WMLT, laminin was found to promote development of oligodendroglial lineage (OL) cells by binding to laminin receptors. Interestingly, laminin could also guide linear axon regeneration via interactions with specific integrins on the axon surface. The WMLT developed here utilizes the unique microstructure and bioactive matrix of DON to create a niche rich in laminin, NT-3 and OL cells to achieve significant structural repair of SCI. Our protocol can help to promote research on repair of nerve injury and construction of neural tissues and organoids that form specific cell niches.

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How NOKOV Contributes to the Research

Future behavioral testing in animals with incomplete SCI would benefit from methods like the Nokov(metric) optical 3D motion capture system that provides a more detailed evaluation of paralyzed limb support and coordination of movement.

Citation Bi-Qin Lai, Yu-Rong Bai, Wei-Tao Han, Bao Zhang, Shu Liu, Jia-Hui Sun, Jia-Lin Liu, Ge Li, Xiang Zeng, Ying Ding, Yuan-Huan Ma, Ling Zhang, Zheng-Hong Chen, Jun Wang, Yuan Xiong, Jin-Hua Wu, Qi Quan, Ling-Yan Xing, Hong-Bo Zhang, Yuan-Shan Zeng,Construction of a niche-specific spinal white matter-like tissue to promote directional axon regeneration and myelination for rat spinal cord injury repair,Bioactive Materials,Volume 11,2022,Pages 15-31,ISSN 2452-199X, https://doi.org/10.1016/j.bioactmat.2021.10.005.

Link https://www.sciencedirect.com/science/article/pii/S2452199X21004564

Cortical representation of multidimensional handwriting movement and implications for neuroprostheses

Keywords

multidimensional handwriting, neural encoding, handwriting trajectory, kinematics and kinetics, brain-computer interface

Abstract

Handwriting brain-computer interfaces (BCIs) have enabled high performance brain-to-text communication for paralyzed individuals. However, the detailed parameters of handwriting movement and their cortical representations remain incompletely understood. Here, we recorded intracortical neural activity from a paralyzed subject and found distinct neural representations for strokes and pen lifts with respect to two-dimensional (2D) velocity on the writing plane, indicating that 2D kinematics alone cannot fully account for the observed neural variance. To address this, we acquired multidimensional handwriting data from healthy subjects, including 3D velocity, grip force, writing pressure, and multi-channel electromyographic (EMG) signals. Incorporating these additional dimensions beyond 2D velocity significantly improved the interpretability of neural signals for both strokes and pen lifts. We further leveraged these additional dimensions to enhance handwriting decoding performance. Together, our findings indicate the motor cortex encodes handwriting as multidimensional movement and highlight the importance of multidimensional features for improving the performance of handwriting BCIs.

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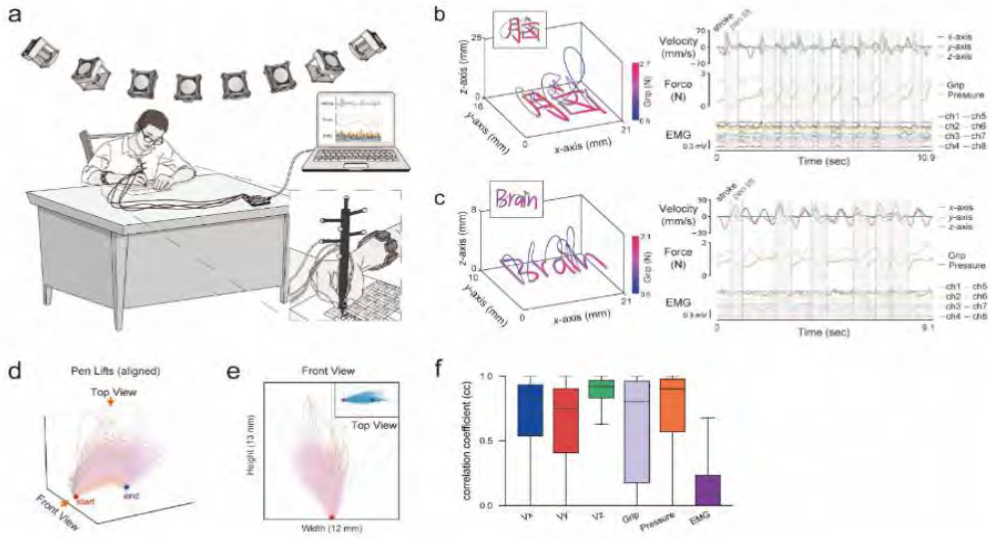

How NOKOV Contributes to the Research

Task and data acquisition: healthy subjects
The six healthy subjects (S1-S6, male, aged 20–30 years) were asked to write the same Chinese characters used for the paralyzed subject. We customized a pen holder using 3D printing technology, which could wrap around a pen (Fig. 3a, inset). There were several branchers extending out of the holder, onto which we afixed 7 markers for optical tracking using a motion capture system with eight lenses (NOKOV, China). The positions of the markers were sampled at a rate of 90 Hz, from which the3D velocity of the pen tip was derived. Three thin-film pressure sensors (diameter 10 mm, Lean star.China) were attached onto the surface of the pen holder, where the thumb, index finger and middle finger hold the pen during handwriting.

Citation Wang Z, Xu G, Yu B, et al. Cortical representation of multidimensional handwriting movement and implications for neuroprostheses[J]. Nature Communications, 2026.

Link https://www.nature.com/articles/s41467-026-70536-7

Design and Experimental Research of Knee Joint Prosthesis Based on Gait Acquisition Technology

Keywords

Gait acquisition; Lower limb prosthesis; Instantaneous movement; Bionic performance

Abstract

Whether the lower limb prosthesis can better meet the needs of amputees, the biomimetic performance of the knee joint is particularly important. In this paper, Nokov(metric) optical 3D motion capture system was used to collect motion data of normal human lower limbs, and the motion instantaneous center of multi-gait knee joint was obtained. Taking the error of knee joint motion instantaneous center line as the objective function, a set of six-bar mechanism prosthetic knee joint was designed based on a genetic algorithm. The experimental results show that the movement trajectory of the instantaneous center of the knee joint is basically similar to that of the human knee joint, so it can help amputees complete a variety of gaits and has good biomimetic performance. Gait acquisition technology can provide important data for prosthetic designers and it will be widely used in prosthetic design and other fields.

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(a) (b) (c)

How NOKOV Contributes to the Research

A Nokov motion information collection system was established, and 30 bone healthy and normal gaiters were selected to collect motion data on their knee and ankle joints. This paper mainly studies the motion status of the lower limbs, namely the motion data of the knee joint and the ankle joint, and then marks the positions shown in Figure 3 in combination with the human body structure.

Citation Zhang Y, Wang E, Wang M, et al. Design and experimental research of knee joint prosthesis based on gait acquisition technology[J]. Biomimetics, 2021, 6(2): 28.

Link https://www.mdpi.com/2313-7673/6/2/28

Detection and Evaluation for High-Quality Cardiopulmonary Resuscitation Based on a Three-Dimensional Motion Capture System: A Feasibility Study

Keywords

cardiopulmonary resusCitation, motion capture, three-dimensional, high-quality, arm posture, training

Abstract

High-quality cardiopulmonary resuscitation (CPR) and training are important for successful revival during out-of-hospital cardiac arrest (OHCA). However, existing training faces challenges in quantifying each aspect. This study aimed to explore the possibility of using a three-dimensional motion capture system to accurately and effectively assess CPR operations, particularly about the non-quantified arm postures, and analyze the relationship among them to guide students to improve their performance. We used a motion capture system (Mars series, Nokov, China) to collect compression data about five cycles, recording dynamic data of each marker point in three-dimensional space following time and calculating depth and arm angles. Most unstably deviated to some extent from the standard, especially for the untrained students. Five data sets for each parameter per individual all revealed statistically significant differences ($p < 0.05$). The correlation between Angle 1′ and Angle 2′ for trained ($rs = 0.203$, $p < 0.05$) and untrained students ($rs = -0.581$, $p < 0.01$) showed a difference. Their performance still needed improvement. When conducting assessments, we should focus on not only the overall performance but also each compression. This study provides a new perspective for quantifying compression parameters, and future efforts should continue to incorporate new parameters and analyze the relationship among them.

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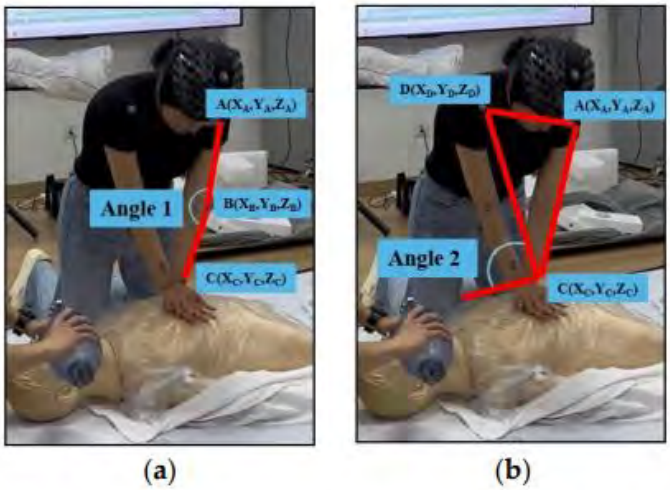

Figure 2. Angle 1 and Angle 2. (**a**) Marker points A, B, and C form Angle 1; (**b**) marker points A, C, and D form a plane, and the plane and the ground form Angle 2.

How NOKOV Contributes to the Research

We used the Resusci-Anne® manikin to simulate an adult cardiac arrest and the infrared light spot motion capture system (Mars series, Nokov, Beijing, China) to obtain the marker point motion data at a collection frequency of 60 Hz. This system includes infrared light cameras and data visualization software (Motion Kinematics & Kinetics Analyzer, Mokka, 0.6.0.0).

Citation Tang X, Wang Y, Ma H, et al. Detection and evaluation for high-quality cardiopulmonary resuscitation based on a three-dimensional motion capture system: a feasibility study[J]. Sensors, 2024, 24(7): 2154.

Link https://www.mdpi.com/1424-8220/24/7/2154

Detection and Evaluation for High-Quality CPR Based on Motion Capture Devices: A Preliminary Test

Keywords

Cardiopulmonary resuscitation; arm position; data-driven; detection; high-quality; motion capture.

Abstract

High-quality cardiopulmonary resuscitation (CPR) is important for successful revival. This test aimed to accurately and effectively assess parameters in CPR operations, particularly focusing on the non-quantified arm posture, to assist instructors in guiding students to enhance the quality of their performance. We used motion capture system (Mars series, Nokov, China) to collect compression data from four trained students about five rounds of CPR, recording dynamic data of each marker in three-dimensional space following time. Using the processed data, we calculated compression depth, frequency, and arm angles. Their performance still needed improvement, and there were variations in data within individuals. This suggests that when instructors conduct assessments, they should focus on not only the overall performance but also each compression. This experiment provides a new perspective for quantifying compression parameters, and future efforts should continue to optimize and incorporate new parameters for assessment.

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Figure 2. Angle 1(left) and Angle 2(right).

How NOKOV Contributes to the Research

We used the infrared light spot motion capture system (Mars series, Nokov, China) to obtain the marker point motion data at a collection frequency of 60 Hz. The motion capture device can record the dynamic coordinates(millimeters) of each marker point in the X, Y, and Z axes in three-dimensional space over time(second).

Citation Tang X, Piao M, Wang Y, et al. Detection and Evaluation for High-Quality CPR Based on Motion Capture Devices: A Preliminary Test[M]//Innovation in Applied Nursing Informatics. IOS Press, 2024: 145-149.

Link https://pubmed.ncbi.nlm.nih.gov/39049242/

Development of a Novel Biomechanical Framework for Quantifying Dynamic Risks in Motor Behaviors During Aircraft Maintenance

Keywords

motion capture, aircraft maintenance, WMSD, risk assessment

Abstract

Aircraft mechanical maintenance involves high loads, repetitive movements, and awkward postures, significantly increasing the risk of work-related musculoskeletal disorders (WMSDs). Traditional static evaluation methods based on posture analysis fail to capture the complexity and dynamic nature of these tasks, limiting their applicability in maintenance settings. To address this limitation, this study introduces a novel quantitative WMSD risk assessment model that leverages 3D motion data collected through an optical motion capture system. The model evaluates dynamic human postures and employs an inverse trigonometric function algorithm to quantify the loading effects on working joints. Experimental validation was conducted through quasi-real-life scenarios to ensure the model's reliability and applicability. The findings demonstrate that the proposed methodology provides both innovative and practical advantages, overcoming the constraints of conventional assessment techniques. Specifically, it enables precise quantification of physical task loads and enhances occupational injury risk assessments. The model is particularly valuable in physically demanding industries, such as aircraft maintenance, where accurate workload and fatigue monitoring are essential. By facilitating real-time ergonomic analysis, this approach allows managers to monitor worker health, optimize task schedules, and mitigate excessive fatigue and injury risks, ultimately improving both efficiency and workplace safety.

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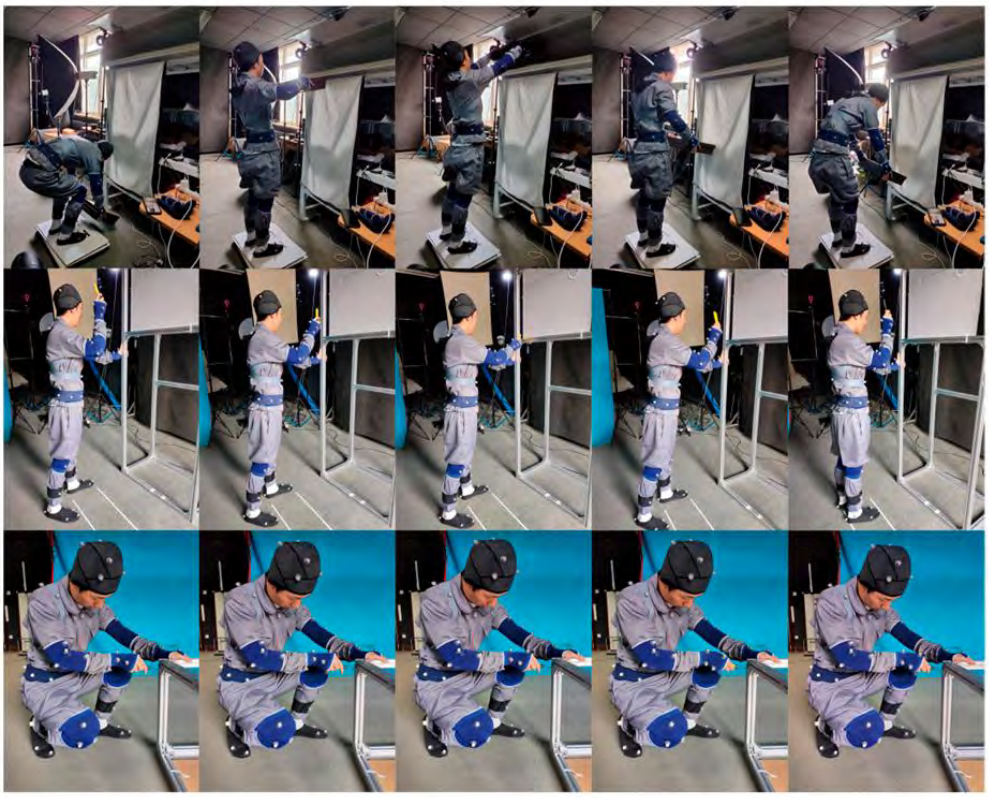

Figure 5. The 3 selected typical aircraft maintenance scenarios.

How NOKOV Contributes to the Research

Motion capture technology deconstructs this complex structure by representing the human skeleton as a series of rigid segments, each possessing mass and connected by joints modeled as hinge structures with specific degrees of freedom. The NOKOV motion capture system employs this approach by defining the human body as a chain-like rigid structure composed of 15 actuated joints, facilitating precise kinematic analysis (Figure 2).

Citation Yu M, Zhao D, Zhang Y, et al. Development of a Novel Biomechanical Framework for Quantifying Dynamic Risks in Motor Behaviors During Aircraft Maintenance[J]. Applied Sciences, 2025, 15(10): 5390.

Link https://www.mdpi.com/2076-3417/15/10/5390

Dynamic modeling of three-dimensional muscle wrapping based on absolute nodal coordinate formulation

Keywords

Musculoskeletal system, Beam-to-beam contact, Forward dynamics, Beam element with variable cross-section, ANCF, Hill-type model

Abstract

Muscle wrapping influences its moment arm and alters the dynamic response of the musculoskeletal system. Conventional musculoskeletal multibody models often simplify muscle wrapping as the shortest path problem, while these models cannot consider the three-dimensional muscular geometry. In comparison, the finite element description of skeletal muscles using three-dimensional solid element discretization is computationally expensive. This paper establishes a novel flexible multibody modeling method of muscle wrapping based on absolute nodal coordinate formulation (ANCF), which can simultaneously deal with its fusiform geometry, distributed inertia, and active contractions. The skeletal muscle is discretized by full-parameterized ANCF beam elements with variable cross section. The three-dimensional shape of the muscle belly can be expressed by an explicit function, and its time-dependent change can be captured via the surface-to-surface contact detection algorithm. The muscle stress contains the effect of Hill-type active–passive contractions, muscular fascia hyperelasticity, and volume constancy based on continuum mechanics description. As a validation, a forward dynamics simulation of the sagittal elbow rotation driven by surface electromyography (sEMG) data was performed and compared with literature data and experimental results. The established numerical method provides an efficient analysis tool to describe muscle-bone force transmissions, presenting an approach for understanding the hidden biomechanics during human locomotion and human–machine interactions.

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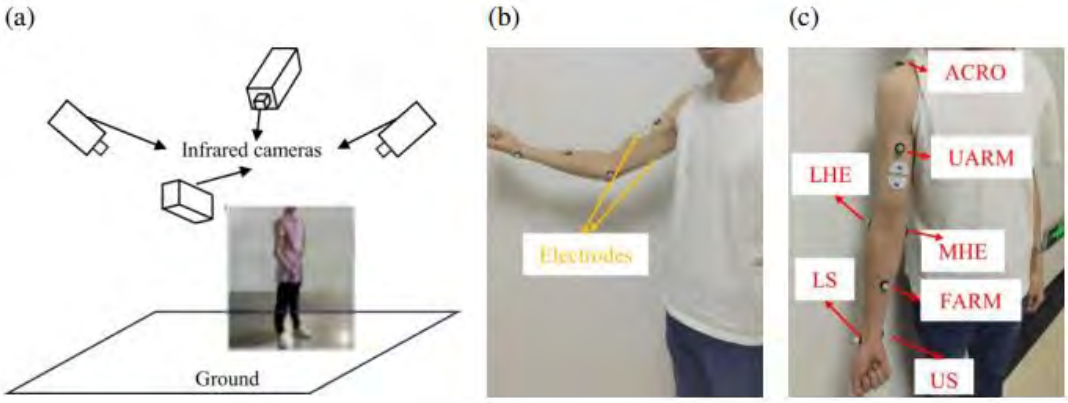

Fig. 18 Sagittal elbow flexion experiment. (**a**) Motion capture system; (**b**) the position of EMG electrodes; (**c**) the position of reflective markers

How NOKOV Contributes to the Research

The kinematic data were recorded using an infrared motion capture system (Nokov Tech., Beijing, China); see Fig.18a. Five markers were placed on the an atomicalland marks, including forward tip of the acromion (ACRO), medial and lateral humeralepicondyles (MHE, LHE), radial and ulnar styloid processes (RS, US). Additional two markers were placed on the right upper arm (UARM) and forearm (FARM), see Fig.18cTake the upper arm as an example, four markers (ACRO, MHE, LHE, UARM)performed rigid body motion approximately during the experiment.

Citation Tang Y, Guo J, Tian Q, et al. Dynamic modeling of three-dimensional muscle wrapping based on absolute nodal coordinate formulation[J]. Nonlinear Dynamics, 2024, 112(15): 13073-13093.

Link https://link.springer.com/article/10.1007/s11071-024-09754-x

Ear2Pos: A Dual-IMU Framework for Full-Body Pose Estimation Using Earbuds

Keywords

3-D human posture estimation, gait analysis, motion processing, sparse inertial sensors

Abstract

In this article, we present Ear2Pos, a novel framework for full-body pose estimation using only two inertial measurement units (IMUs) integrated into earbuds. Unlike traditional motion capture systems requiring multiple sensors, Ear2Pos leverages a minimal setup to achieve high-accuracy 3-D motion reconstruction. The system incorporates a dual-coordinate framework and Transformer-based modeling to predict joint positions and rotations. Additionally, we propose a personalized skeletal parameterization mechanism, utilizing extracted bone lengths from a single image to enhance individual adaptability. Extensive evaluations demonstrate that Ear2Pos achieves state-of-the-art accuracy in pose estimation when using two sensors, outperforming other methods in upper body motion prediction with an average joint position error of 5.04 cm. Furthermore, we explore clinical applications, particularly in gait analysis for cervical spondylotic myelopathy (CSM) patients, showcasing the framework's potential for rehabilitation assessment. These findings indicate that Ear2Pos is a promising lightweight solution for noninvasive motion capture, offering robust performance in both research and real-world applications.

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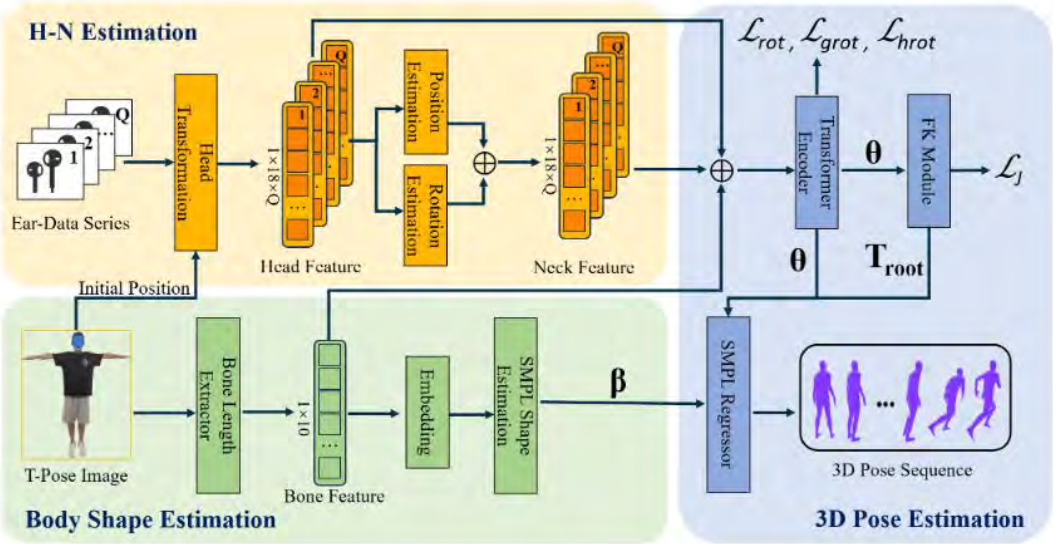

Fig. 1. Overview of system architecture.

How NOKOV Contributes to the Research

To better evaluate the practical value of Ear2Pos, we collected a dataset, GSet. GSet is a real-world gait dataset collected in our experiments, aimed at learning gait characteristics from different individuals and CSM patients. Using the NOKOV optical motion capture system, we collected gait data from four healthy individuals and two CSM patients.

Citation Wang H, Yang Z, Wang H, et al. Ear2Pos: A Dual-IMU Framework for Full-Body Pose Estimation Using Earbuds[J]. IEEE Internet of Things Journal, 2025.

Link https://ieeexplore.ieee.org/document/11016036

Effect of different ankle braces on lower extremity kinematics and kinetics following special-induced fatigue for volleyball players with functional ankle instability

Keywords

FAI， Specific fatigue protocol， High-risk movement， Ankle support， Biomechanics

Abstract

Background: The aim of this study is to examine the effects of different ankle braces on functional ankle instability (FAI) participants following special-induced fatigue, which will provide advice for preventing ankle sprains in volleyball game. Methods: A total of 18 male collegiate volleyball players with FAI were recruited. The kinematics and kinetics data were acquired from the participants during single-leg drop landing using the infrared motion capture system (Mars2H, Nokov, China) and the force platform (Bertec, USA). A 2 × 2 within subjects design ANOVA was adopted to analyze the data. Results: Whether fatigue or not, soft and semi-rigid brace reduced the ankle inversion ($P = 0.025$). Moreover, soft brace reduced the sagittal range of motion (ROM) of the ankle joint before fatigue ($P = 0.05$). In addition, the semi-rigid brace shortened the time to stability in the medial and lateral directions ($P = 0.039$) as well as the vertical directions ($P < 0.001$). The semi-rigid brace reduced the ground reaction force post-fatigue ($P = 0.001$). Conclusion: Soft ankle brace reduced the sagittal range of motion pre-fatigue. Since volleyball requires athletes to jumping and landing repeatedly, and the ankle sagittal ROM was an important cushion during landings. Thus, soft ankle brace might result in overuse injury for lower extremity. However, the semi-rigid ankle brace increased the dynamic stability in the medial and vertical directions, and reduced the ankle inversion angle and forward ground reaction force post-fatigue. This ensured that the volleyball player's ankle was in a neutral position during landing, reducing the risk of excessive inversion caused by contact with the opposing player during spike and block.

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Fig. 2. Testing maneuvers.

How NOKOV Contributes to the Research

Methods: A total of 18 male collegiate volleyball players with FAI were recruited. The kinematics and kinetics data were acquired from the participants during single-leg drop landing using the infrared motion capture system (Mars2H, Nokov, China) and the force platform (Bertec, USA). A 2 ×2 within subjects design ANOVA was adopted to analyze the data.

Citation Zhang Z, Zhang M. Effect of different ankle braces on lower extremity kinematics and kinetics following special-induced fatigue for volleyball players with functional ankle instability[J]. Heliyon, 2023, 9(6).

Link https://www.cell.com/heliyon/fulltext/S2405-8440(23)03587-9

Effects of Dynamic IMU-to-Segment Misalignment Error on 3-DOF Knee Angle Estimation in Walking and Running

Keywords

IMU; DPSO; joint constraint; dynamic IMU-to-segment alignment

Abstract

The inertial measurement unit (IMU)-to-segment (I2S) alignment is an important part of IMU-based joint angle estimation, and the accurate estimation of the three degree of freedom (3-DOF) knee angle can provide practical support for the evaluation of motions. In this paper, we introduce a dynamic weight particle swarm optimization (DPSO) algorithm with crossover factor based on the joint constraint to obtain the dynamic alignment vectors of I2S, and use them to perform the quaternion-based 3-DOF knee angle estimation algorithm. The optimization algorithm and the joint angle estimation algorithm were evaluated by comparing with the optical motion capture system. The range of 3-DOF knee angle root mean square errors (RMSEs) is 1.6°–5.9° during different motions. Furthermore, we also set up experiments of human walking (3 km/h), jogging (6 km/h) and ordinary running (9 km/h) to investigate the effects of dynamic I2S misalignment errors on 3-DOF knee angle estimation during different motions by artificially adding errors to I2S alignment parameters. The results showed differences in the effects of I2S misalignment errors on the estimation of knee abduction, internal rotation and flexion, which indicate the differences in knee joint kinematics among different motions. The IMU to thigh misalignment error has the greatest effect on the estimation of knee internal rotation. The effect of IMU to thigh misalignment error on the estimation of knee abduction angle becomes smaller and then larger during the two processes of switching from walking to jogging and then speeding up to ordinary running. The effect of IMU to shank misalignment error on the estimation of knee flexion angle is numerically the largest, while the standard deviation (SD) is the smallest. This study can provide support for future research on the accuracy of 3-DOF knee angle estimation during different motions.

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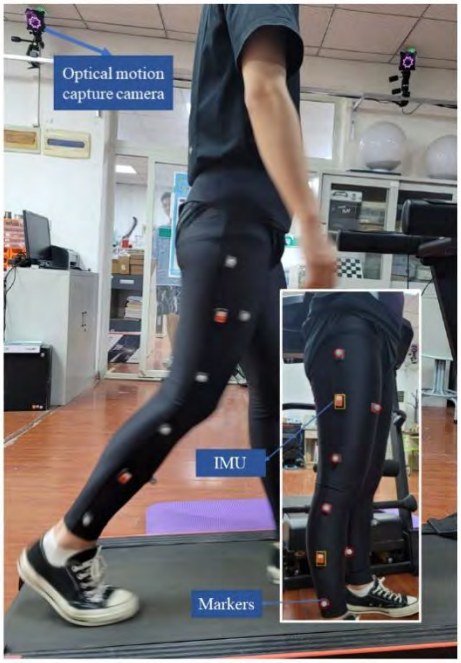

How NOKOV Contributes to the Research

Twelve high-speed infrared cameras from Nokov (Beijing, China) form an optical motion capture system to capture the position of markers, and both systems operate at 60 Hz. The three non-coplanar markers are set on the thighs and shank of both legs to define the attached rigid bodies, and the rotational data of each segment is output through Nokov's software.

Citation Jiang C, Yang Y, Mao H, et al. Effects of dynamic IMU-to-segment misalignment error on 3-DOF knee angle estimation in walking and running[J]. Sensors, 2022, 22(22): 9009.

Link https://www.mdpi.com/search?q=Effects+of+Dynamic+IMU-to-Segment+Misalignment+Error+on+3-DOF+Knee+Angle+Estimation+in+Walking+and+Running

Effects of Mental Fatigue on Trunk and Knee Kinetics and Kinematics During Unanticipated Stop-Jump in Amateur Soccer Players

Keywords

ACL, mental fatigue, anticipated, soccer, stop-jump

Abstract

Background:Physical fatigue in soccer has been considered a risk factor for anterior cruciate ligament (ACL) injury, while mental fatigue could lead to decision-making errors and induce injuries. However, there is a lack of research on the combined effects of mental fatigue and decision making on lower limb biomechanics.

Hypotheses:(1) Mental fatigue leads to a decrease in trunk flexion angle and knee flexion angle when touching the ground, as well as an increase in knee valgus moment and horizontal backward ground-reaction force (GRF) under unexpected conditions, which may lead to an increase in knee joint load. (2) The combined effects of mental fatigue and decision making lead to increased knee extension moment and valgus moment, leading to characteristics that may increase the risk of injury.

Study Design:Descriptive laboratory study.

Methods:Twenty male amateur soccer players were recruited as participants. Mental fatigue was induced through a 45-minute Stroop task, where the color of the screen changed randomly using a self-made infrared induction synchronous trigger to create different anticipated state scenes. A 12-lens infrared spot 3-dimensional (3D) motion capture system and 3D force plates were used to collect kinematic and dynamic data from the trunk and knee joints.

Results:Mental fatigue and expected state demonstrated significant interaction effects on knee flexion angle and peak horizontal posterior GRF. At the initial contact, knee flexion angle (P = .002) and trunk flexion angle (P = .04) were significantly decreased post-mental fatigue compared with pre–mental fatigue. In the unanticipated condition, knee valgus moment was significantly increased (P = .014). At the first peak of horizontal posterior GRF, compared with pre–mental fatigue, the trunk flexion angle (P = .04) and knee flexion angle (P = .017) were significantly decreased, and the peak horizontal posterior GRF (P = .03) and knee valgus moment were significantly increased postfatigue (P = .03).

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Conclusion:Soccer players demonstrated a more upright landing posture post–mental fatigue, and unanticipated conditions negatively affected trunk and knee movement patterns, potentially increasing the risk of ACL injury. The interaction of mental fatigue with unexpected factors did not appear to amplify the risk of ACL injury.

Clinical Relevance:This study elucidates the effect of mental fatigue and decision making on the ACL. These risk factors may be incorporated into ACL prevention strategies.

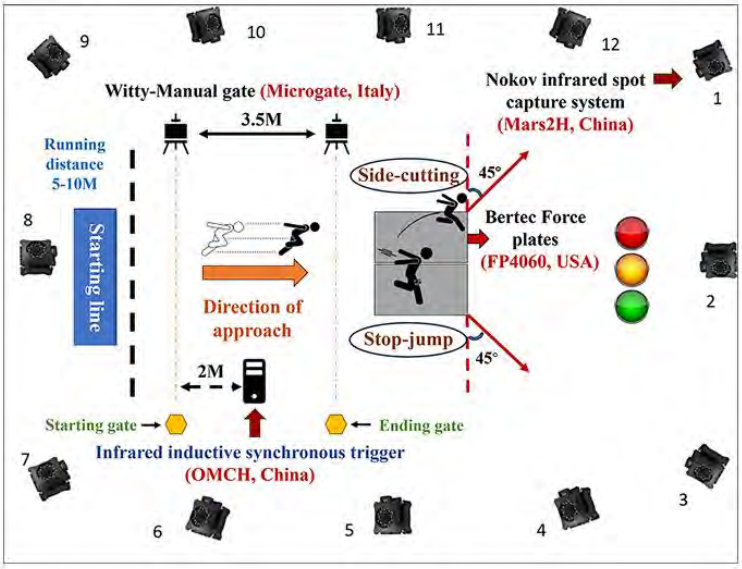

Figure 2. Test-site schematic diagram.

How NOKOV Contributes to the Research

Experimental process: the participant passed through the infrared induction synchronous trigger 2 m behind the starting gate, then 1 of the 3 colors of red, yellow,and green appeared randomly on the computer screen and the participant made corresponding actions according to the color. Laboratory equipment included an infrared induction synchronous trigger, a 12-lens infrared spot 3Dmotion capture system (Mars2H; Nokov), 3D force plates(FP4060; Bertec), and a Witty-Manual gate (Microgate).

Citation Yang R, Zhang M, Wang Z, et al. Effects of Mental Fatigue on Trunk and Knee Kinetics and Kinematics During Unanticipated Stop-Jump in Amateur Soccer Players[J]. Orthopaedic Journal of Sports Medicine, 2025, 13(5): 23259671251338239.

Link https://journals.sagepub.com/doi/full/10.1177/23259671251338239

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Footstrike evaluation in male runners: A comparison of lateral and medial video views against traditional motion capture

Keywords

Gait, Kinematics, Validation, Landing pattern

Abstract

Footstrike evaluation is essential for understanding running biomechanics and is often performed in research and clinical settings using 2D video analysis. However, whether it is appropriate to analyse both right-left footstrike patterns from a single sagittal plane video is unclear. This study compared medial and lateral video views in assessing footstrike pattern and footstrike angle, using a motion capture system as the gold standard. We analyzed 4,800 footfalls from 20 healthy recreational runners during self-paced treadmill running, recruited through convenient sampling. Footstrike angle agreement was evaluated using Bland-Altman analysis, intraclass correlation coefficients (ICC), and root mean square error (RMSE). The mean difference in footstrike angle between the gold standard and lateral view was 0.40° (95% limits of agreement: 6.05° to −5.25°), while the medial view showed a mean difference of −1.31° (95% limits: 8.37° to −10.99°). ICC values indicated excellent agreement for both lateral (0.979) and medial (0.940) views to the gold standard. RMSE was lower for the lateral (2.91°) than medial (5.11°) view, suggesting greater precision. Footstrike pattern classification was assessed using Cohen's kappa, revealing substantial agreement for the lateral view ($\kappa = 0.785$, $p < 0.001$) and good agreement for the medial view ($\kappa = 0.606$, $p < 0.001$). These results indicate that while both views demonstrate strong agreement, the lateral view aligns more closely with the gold standard in continuous and categorical assessments. Our findings suggest lateral video analysis may be preferable for footstrike evaluation in applied and clinical settings.

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How NOKOV Contributes to the Research

Marker trajectory data and video recordings were simultaneously captured. A motion capture system (Mars2H, Beijing NOKOV® Science & Technology Co., Ltd., Beijing, China) with 12 infrared cameras sam-pling at 240 Hz was used to record marker trajectory. The two smart-phones captured lateral and medial side video footage at the same sampling rate. During the trials, participants wore their usual running shoes. A 5-minute rest period was provided between trials.

Citation Mo S, Chu A S Y, Shao S, et al. Footstrike evaluation in male runners: A comparison of lateral and medial video views against traditional motion capture[J]. Journal of Biomechanics, 2025: 112865.

Link https://www.sciencedirect.com/science/article/abs/pii/S002192902500377X

Gait phases recognition based on lower limb sEMG signals using LDA-PSO-LSTM algorithm

Keywords

Gait phase recognition; Surface electromyography (sEMG); Long short-term memory (LSTM); Particle swarm optimization (PSO); Linear discriminant analysis (LDA)

Abstract

Gait phases are widely used in exoskeleton movement control. Surface electromyography (sEMG) is predictive and plays an important role in gait phase recognition. The purpose of this study is to improve the stability and accuracy of gait recognition methods based on the sEMG signals of lower limbs. First, we presented a LDA-PSO-LSTM algorithm based on feature combination selection and verified its recognition accuracy through experiments. LDA-PSO-LSTM had an average recognition rate of 94.89% and a maximum accuracy of 97.02%. Second, we tested and compared the recognition accuracy of LDA-LSTM (92.17%). Experiments showed that the PSO optimization model had good recognition performance. Finally, we compared LDA-LSTM with all classifier combinations and concluded that the LDA-LSTM method has the highest recognition rate among a series of method combinations. The results indicated that LDA-PSO-LSTM as a classification model has apparent advantages in gait recognition. LDA-PSO-LSTM provides more accurate gait phase results for lower limb exoskeleton control. This method is beneficial to the development of the exoskeleton gait recognition system.

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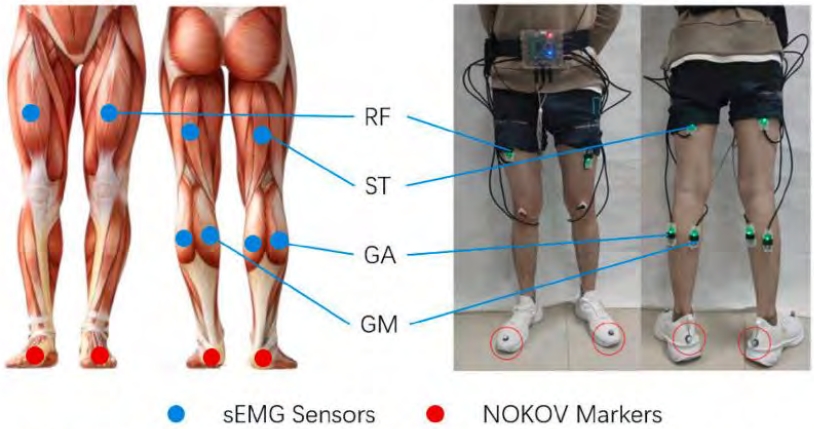

Fig. 6. The location of the sEMG sensors and the optical markers. Four optical markers were placed at the toe and heel of each foot, and eight sEMG sensors were placed in the lower limb.

How NOKOV Contributes to the Research

We designed a customized device to measure subjects' sEMG and optical signals when walking on a treadmill. The system's hardware included a treadmill, a computer, a Bluetooth transmitter, a 5 V power supply, a self-designed data acquisition board, a pair of reference electrodes, eight sEMG signal sensors, several droplet-type electrode sheets, eight NOKOV motion capture cameras Mars 12H (NOKOV motion capture system, Beijing, China), and four reflective markers.

Citation Cai, Shibo, et al. "Gait phases recognition based on lower limb sEMG signals using LDA-PSO-LSTM algorithm." Biomedical Signal Processing and Control 80 (2023): 104272.

Link https://www.sciencedirect.com/science/article/abs/pii/S1746809422007261

GaitFormer: Leveraging dual-stream spatial–temporal Vision Transformer via a single low-cost RGB camera for clinical gait analysis

Keywords

Gait analysis; Human pose estimation; Healthcare; Vision Transformer; Single RGB camera

Abstract

Gait analysis is an essential technique in treating patients with lower limb dysfunctions. Traditional methods often rely on expensive and complex equipment, such as wearable body sensors and a multi-camera with marker tracking system. Aiming for a more cost-effective yet accurate alternative, this paper introduces GaitFormer, a novel approach that leverages Vision Transformer (ViT) for gait analysis using minimal, non-invasive equipment, i.e. a single low-cost RGB camera. Initially, a unique dataset using a multi-camera system with marker tracking, comprising 6 walking patterns gathered from 80 volunteers is developed. The ViT-based GaitFormer is then proposed to automatically recognize human walking patterns through a single RGB camera. GaitFormer comprises hybrid networks for each step, including: (i) a cascaded convolutional 2D human key points estimation network; (ii) a ViT-based dual-stream spatial – temporal network extending the information of human key points into 3D; (iii) leveraging specific lower limb key joints' angle features for clinical gait analysis, capturing the geometric, kinematic, and physical attributes of human motion; (iv) employing a pure self-attention-based classification network to recognize clinical human walking patterns. The experiments are designed to comprehensively validate each step against various related baseline methods and multi-camera tracking system, with results demonstrating the promising performance of GaitFormer as an affordable, precise, and integrated solution. To the best of our knowledge, GaitFormer is the first hybrid CNN- and ViT-based end-to-end solution via low-cost device for clinically valuable gait analysis.

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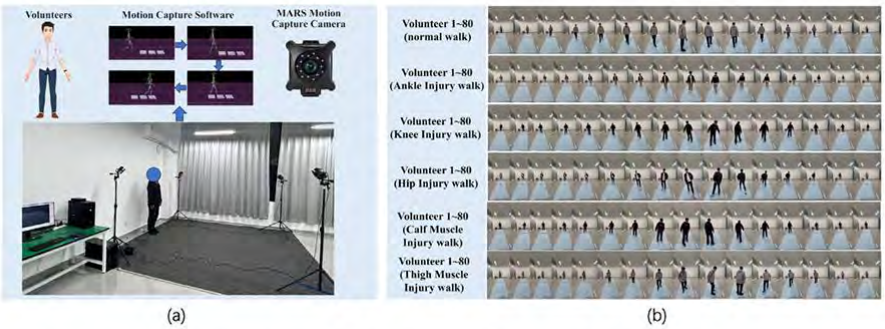

Fig. 2. The illustration of dataset development hardware and example frames of dataset with multiple volunteers and multiple walking patterns.

How NOKOV Contributes to the Research

Additionally, a NOKOV metric optical 3D motion capture system was employed to gather detailed gait data from an individual, serving as a benchmark for our analysis,1 which is briefly illustrated in Fig. 2(a).

Citation Jiabao Li, Ziyang Wang, Chengjun Wang, Wenhang Su,GaitFormer: Leveraging dual-stream spatial–temporal Vision Transformer via a single low-cost RGB camera for clinical gait analysis, Knowledge-Based Systems,Volume 295,2024,111810,ISSN 0950-7051, https://doi.org/10.1016/j.knosys.2024.111810.

Link https://www.sciencedirect.com/science/article/abs/pii/S0950705124004441

Human Control Intent Inference Using ESNs and Input-Tracking Based Inverse Model Predictive Control

Keywords

Movement intent inference, Model predictive control, Echo state Networks

Abstract

Acquiring human motor control strategies or intents is helpful for clinical research, wearable robotic device design and human-robot cooperation control. The state-of-art method is to construct an optimal control framework which is capable to predict the target motion and take the cost function as the potential control intents. Aimed to solve this problem, an echo state networks based state space model (SSM) extraction method and input-tracking inverse MPC algorithm are proposed in this paper. By applying Taylor expansion around an operating point, it is convenient to acquire the SSM via the SSM extraction method and more detailed information about human musculoskeletal system is preserved. Setting the target of the upper level optimization as input-tracking is more rational than conventional output-tracking structure, given the consideration that human motion control is a multiple-solution problem. The effectiveness of the proposed method is verified in both simulation and real-world experiments.

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How NOKOV Contributes to the Research

It is important to acquire the accurate inputs and outputs data for ESNs training. Normally, the proper inputs of a human movement control are muscle activations, muscle tendon force or joint torques. The open source program of OpenSim provides an alternative indirect approach to obtain these inputs. In order to calculate the joint torques or muscle tendon forces, kinematics data and, if available, the external forces are required. These required inputs can be easily accessed via motion capture system (Nokov, Duliang Technology Co. Ltd., CHN) and 6-axis force platform (BMS400600-1K, AMTI, USA). In this paper, ankle,knee, hip and lumbar joint torques are obtained through OpenSim inverse dynamic function and calibrated by Residual Reduction Algorithm function.

Citation Gong P, Pang M, Xiang K, et al. Human Control Intent Inference Using ESNs and Input-Tracking Based Inverse Model Predictive Control[C]//International Conference on Intelligent Robotics and Applications. Cham: Springer International Publishing, 2021: 642-653.

Link https://link.springer.com/chapter/10.1007/978-3-030-89095-7_61

Human Gait Analysis Based on OpenSim

Keywords

Lower limb exoskeleton; OpenSim; Human gait; Simulation; NoKov optical 3D motion

Abstract

The gait motion is fundamental human locomotion that is associated with the human lower limb. Considering the complex structural characteristics of gait, the major challenge is the dynamics model's accuracy and certainty. This paper pro- poses a method for analyzing human gait in walking. This paper adopted the NoKov optical three-dimensional motion capture system to collect human gait data, built dynamics and kinematics exoskeleton model, and then designed inverse kinematics algorithms. To obtain human gait characteristics, we established a high-precision human lower limb musculoskeletal model in OpenSim, and then imported gait data into the model for kinematics and dynamics simulation. To verify the effectiveness of the proposed method, in this paper, joint angles changes obtained through inverse kinematics analysis of MATLAB are compared with joint angle changes simulated by OpenSim musculoskeletal model.

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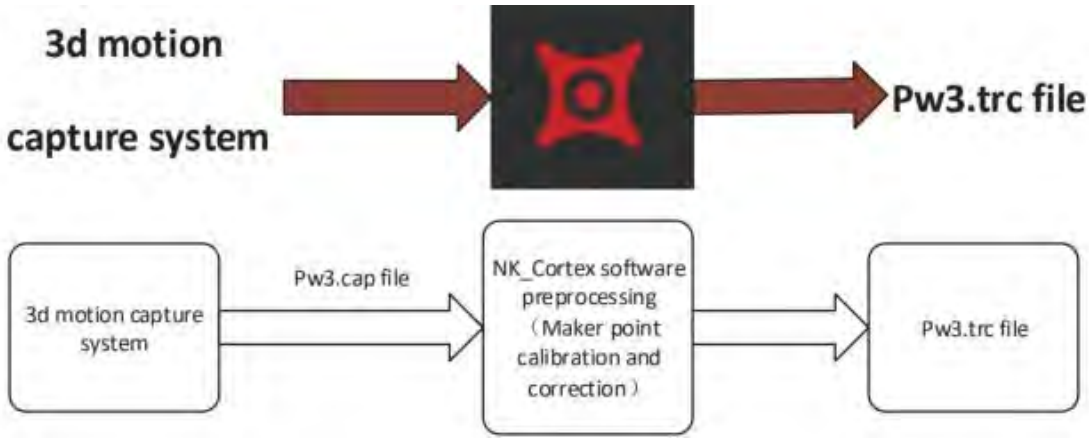

How NOKOV Contributes to the Research

The gait motion is fundamental human locomotion that is associated with the human lower limb. Considering the complex structural characteristics of gait, the major challenge is the dynamics model's accuracy and certainty. This paper pro- poses a method for analyzing human gait in walking. This paper adopted the NOKOV optical three-dimensional motion capture system to collect human gait data, built dynamics and kine- matics exoskeleton model, and then designed inverse kinematics algorithms. To obtain human gait characteristics, we established a high-precision human lower limb musculoskeletal model in OpenSim, and then imported gait data into the model for kinematics and dynamics simulation. To verify the effectiveness of the proposed method, in this paper, joint angles changes obtained through inverse kinematics analysis of MATLAB are compared with joint angle changes simulated by OpenSim musculoskeletal model.

Citation Yu J, Zhang S, Wang A, et al. Human gait analysis based on OpenSim[C]//2020 International Conference on Advanced Mechatronic Systems (ICAMechS). IEEE, 2020: 278-281.

Link https://ieeexplore.ieee.org/abstract/document/9310111

Impact of spinal-hip types on gait patterns in patients with end-stage hip disease

Keywords

Spinal-hip types, Gait analysis, Spatiotemporal, Kinematic parameters, Sagittal balance, Gait profile score

Abstract

Background

Patients with end-stage hip disease are classified into distinct spinal-hip types according to sagittal spinal-hip parameters. Each type employs specific compensatory strategies to maintain balance, but the associated alterations in gait patterns remain unclear. This study characterized the gait differences among patients with different spinal-hip types.

Methods

This prospective observational study used EOS imaging to obtain full-length sagittal images and classify patients into spinal-hip types. The study included 10 patients in each type (A, B, and C) and 10 healthy controls. Gait analysis was performed to evaluate the spatiotemporal and kinematic parameters, followed by the gait profile score (GPS) analysis. The Kruskal–Wallis test was used to compare relevant parameters across the four groups, with post-hoc comparisons conducted using the Bonferroni method.

Results

Significant differences among the types were observed in stride length (\\(P=0.003\\)), stance phase percentage (\\(P=0.001\\)), and swing phase percentage (\\(P<0.001\\)), with type C showing the shortest stride and type A exhibiting the shortest stance phase. The sagittal range of motion (ROM) of the pelvis and hip varied significantly across the gait cycle (both \\(P<0.001\\)), with type A exhibiting the largest pelvic ROM and the smallest hip ROM. Types A and C showed lower sagittal center of mass displacement during the stance phase (\\(P<0.001\\)). Type A exhibited the most restricted knee ROM during the swing phase (\\(P<0.001\\)). The GPS was highest in type A, followed by type C, while type B and healthy controls had the lowest scores (\\(P<0.001\\)).

Conclusions

Patients with different spinal-hip types exhibited distinct gait adaptations to compensate for sagittal deformities. Patients with severe sagittal imbalance exhibited compensatory increased pelvic swing and demonstrated diminished functional scores. Preoperative assessment is

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essential for optimizing total hip arthroplasty outcomes and guiding rehabilitation.

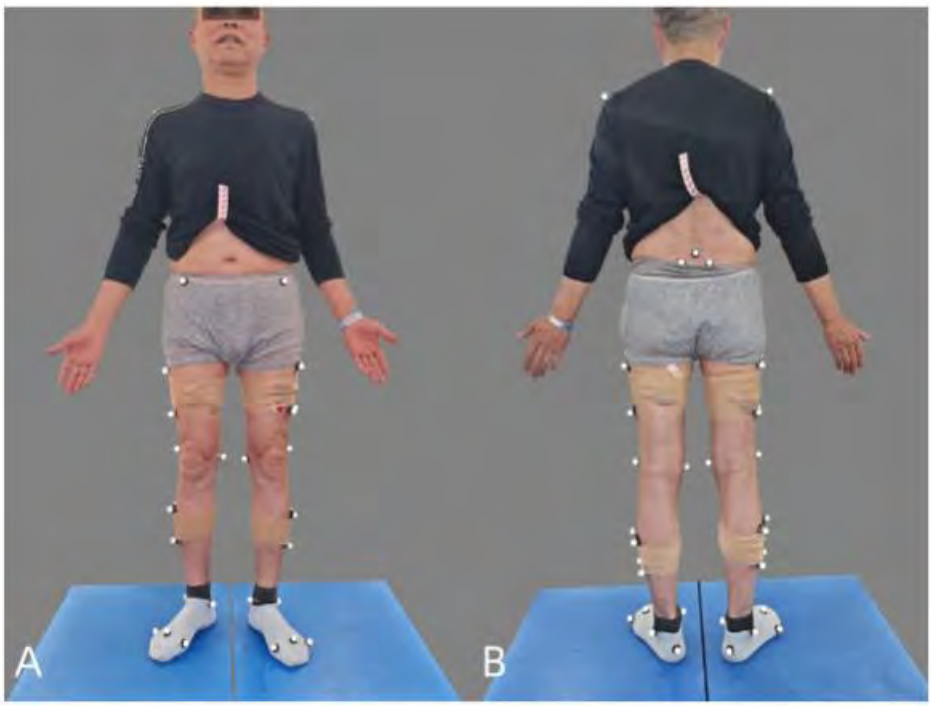

Fig. 2 Participant after placing the fluorescent markers. **A)** The front of the participant. **B)** The back of the participant

How NOKOV Contributes to the Research

Data collection
Each participant completed five walking trials at a self-selected speed, barefoot. Reflective markers were placedbilaterally on anatomical landmarks, including the acro-mions, anterior and posterior superior iliac spines, femoral condyles, malleoli, metatarsophalangeal joints, toes,and heels. Additional markers were positioned at theL4-L5 intersection and on bilateral thigh and shank clusters (Fig. 2). Three-dimensional (3D) marker trajectorieswere captured using an eight-camera motion analysis system (Nokov, China) at 200 Hz. Ground reaction forces(GRFs)were recorded with two force plates (Kunwei,China) at 1000 Hz, with kinematic and force data synchronized for analysis.

Citation Ma Z, Fu S, Wu X, et al. Impact of spinal-hip types on gait patterns in patients with end-stage hip disease[J]. Journal of Orthopaedic Surgery and Research, 2025, 20(1): 387.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001473104100003

IMU-based Real-time Biofeedback Wristband with Automatic Sensor-to-segment Calibration for Arm Swing Training

Keywords

Arm swing, biofeedback, inertial measurement unit (IMU), sensor-to-segment calibration, wristband

Abstract

Arm swing during walking is significant as it enhances gait stability and reduces energy expenditure. Reduced arm swing in patients with Parkinson's disease (PD) or the elderly causes poor mobility and higher fall risk. This article develops an IMU-based real-time biofeedback wristband with an automatic sensor-to-segment calibration algorithm for arm swing training. The real-time algorithm detects key frames and calculates the sensor-to-segment alignment transformation, then monitors arm swing motion, and provides vibration feedback when insufficient arm swing is detected. Validation experiments were performed to assess the accuracies of arm swing angle, angular velocity estimations, and the effectiveness of real-time biofeedback. Seventeen subjects wore wristbands and optical markers on their arms while performing slow, normal, and fast walking on a treadmill. Arm swing angle, angular velocity, and range of motion were extracted with and without the proposed calibration method. An additional wristband manually aligned with the forearm was used for comparison and an optical motion capture (OMC) system was utilized for reference. For the proposed method with automatic calibration, the root-mean-square errors (RMSEs) of the estimated continuous swing angle and angular velocity were 2.1° and 12.8° /s, respectively, which were 46% and 58% of those estimated with the manually aligned wristband. In real-time feedback experiments, subjects exhibited a notable increase in arm swing amplitude given the stimulus from vibration feedback. The developed wristband could serve as an effective training and easy-to-use device, which has the potential for PD patients to increase their arm swing amplitude during walking.

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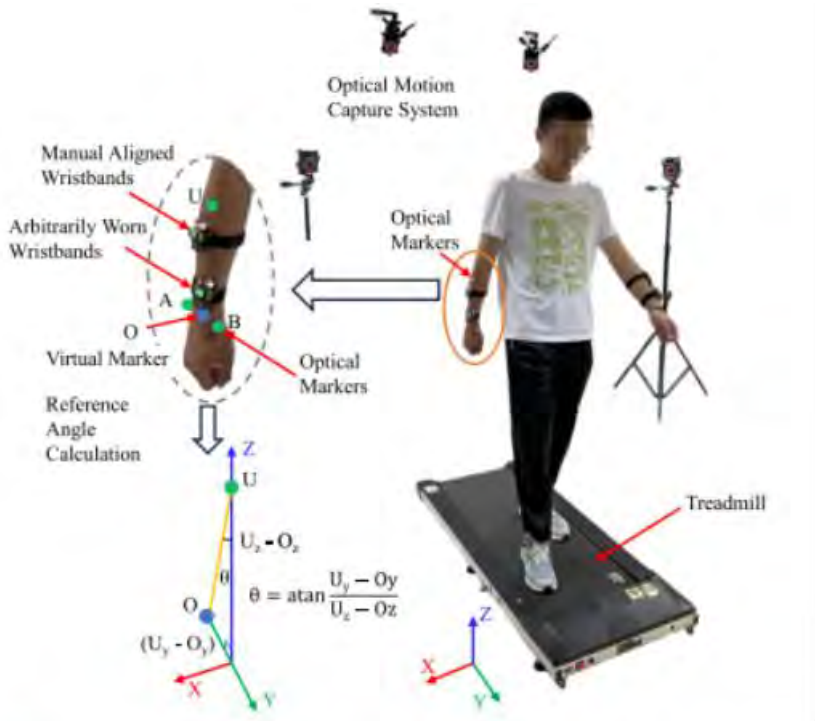

Fig. 5. Experimental scenario. The subject wore two wristbands on each forearm for arm motion monitoring. The lower wristband was arbitrarily worn and thus needed sensor-to-segment calibration. The upper one was manually aligned with the forearm. Its roll angle was directly regarded as the arm swing angle. Three optical markers were pasted on the arm and were used for reference arm swing angle and angular velocity calculation.

How NOKOV Contributes to the Research

An OMC system with 12 cameras (Mars 2H, NOKOV, Beijing, China) was used as the reference system, and the sampling rate was also 100 Hz. We placed three markers on each arm. Specifically, markers were pasted on the lateral epicondyle of the humerus (U), the radius-styloid process (B), and the ulna-styloid process (A) of the arm. These markers constituted a rigid triangle.

Citation Fan B, Chen J, Tan C, et al. IMU-based Real-time Biofeedback Wristband with Automatic Sensor-to-segment Calibration for Arm Swing Training[J]. IEEE Sensors Journal, 2025.

Link https://ieeexplore.ieee.org/abstract/document/10847704

Investigation of pre-crash avoidance kinematics in pedestrians of different ages through volunteer experiment and scaling methodology

Keywords

Pedestrian safety, age, pre-crash behavior, collision area identification, highly automated vehicles

Abstract

Objective:Understanding pedestrians' pre-crash avoidance kinematics is crucial for improving the identification of potential collision areas in interactions with highly automated vehicles (HAVs). Age significantly influences pedestrian avoidance velocity and the subsequent crash risks. However, current active safety systems in HAVs often overlook the influence of pedestrians' avoidance velocity and age on imminent accidents. This study analyzes how age affects pedestrian avoidance velocity and explores the incorporation of these factors in pre-crash scenarios to identify potential collision areas between pedestrians and vehicles.Methods:Due to the infeasibility of measuring pedestrian avoidance behaviors in real-world pre-crash scenarios, we designed an indoor experimental platform replicating emergency crossroad scenarios to prompt subjects to mimic avoidance behaviors. 7 young and 7 middle-aged subjects participated in the experiment, resulting in a collection of 306 forward-avoidance, 297 backward-avoidance, and 42 normal-walking posture sequences. We developed a scaling approach integrating pedestrian kinematics and muscle physiology to establish a velocity-mapping relationship between young and middle-aged groups. Finally, we proposed an identification method for potential collision areas that considers pedestrians' age and avoidance velocity.Results:Middle-aged subjects required more time for natural avoidance actions averaging 0.15 s for forward and 0.25 s for backward avoidance, compared to their younger counterparts. While the forward avoidance velocity of the middle-aged subjects exhibited an average decrease of 0.3 m/s compared to young subjects, their backward avoidance velocity remained nearly identical. Overall, middle-aged subjects have a larger potential collision area than young participants. Pedestrians who actively avoid vehicles have a smaller potential collision area compared to those who remain normal walking.Conclusions:We developed an indoor simulated pre-crash scenario experiment and a scaling approach to reveal the correlation between pedestrian avoidance velocity and age.

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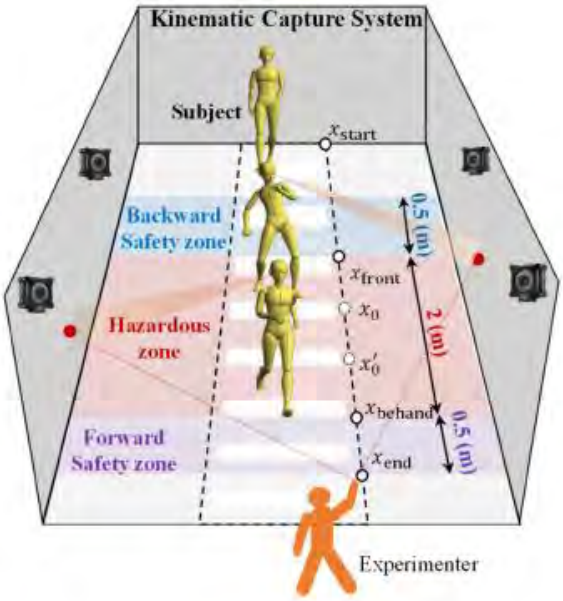
This method can be further applied to obtain the avoidance velocity of elderly pedestrians. Additionally, we validate the effect of these factors in assessing potential collision areas. The decrease in avoidance velocity highlights a larger potential collision area for middle-aged pedestrians when interacting with vehicles. Such facts and data shall be appropriately considered in developing intelligent protection systems for pedestrians.



(c)

Figure 1. (a) Forward avoidance behavior in real traffic accident; (b) backward avoidance behavior in real traffic accident; (c) simulated scenario experiment (the random red light from the experimenter represents a vehicle approaching perpendicular to the pedestrian's direction; the red zone represents the collision area; the blue and purple zones represent safe areas for pedestrians after avoiding approaching vehicles.

How NOKOV Contributes to the Research

The kinematic capture system (No. Mars 2H; BeijingNokov Science & Technology Co. , Ltd) includes 24 cameras with a sampling frequency of 60 Hz, 54 on-body markers, and a data processing software. During the experiment, the cameras were positioned on fixed trestles at the room's edges to record subjects' kinematic information. Additionally, 54 on-body markers were strategically placed to allow the cam-era to capture the subjects' movements throughout the entire event. The pedestrian velocity was then extracted from the data collected at the center of the pelvis.

Citation Liu S, Li Q, Sun H, et al. Investigation of pre-crash avoidance kinematics in pedestrians of different ages through volunteer experiment and scaling methodology[J]. Traffic Injury Prevention, 2025, 26(3): 281-290.

Link https://www.tandfonline.com/doi/abs/10.1080/15389588.2024.2408402

Neural encoding of multidimensional handwriting movements for brain-computer interfaces

Keywords

brain-computer interfaces (BCI), high-performance decoding, neural encoding, multidimensional handwriting movements

Abstract

Neural representations of handwriting persist even years after paralysis, which was previously employed to build high performance brain-computer interfaces (BCI) for brain-to-text communication. However, handwriting was traditionally viewed as two-dimensional (2D) movements, ignoring other key kinematic and kinetic dimensions. How brain encodes these additional dimensions during handwriting and the potential of this information to enhance BCI performance were largely unexplored. Here, we recorded intracortical neural signals from a paralyzed individual engaged in handwriting imaginary and tried to align these signals with the multidimensional handwriting movements from healthy subjects. We achieved successful decoding of neural signals from the paralyzed individual, enabling reconstruction of 2D handwriting trajectories with high accuracy. We then characterized handwriting from heathy subjects as multidimensional movements which include 3D velocity of pen tip, pen grip strength, pen tip pressure on the paper, and 8-channel electromyography (EMG) on forearm. Employing a neural encoding model, we found that more variance of the neural signals could be accounted by these additional variables, suggesting brain encodes handwriting in multiple dimensions rather than solely in 2D. Together, these results shed light on the complex neural mechanisms underlying handwriting, offering new insights into the potential for improving related BCI applications.

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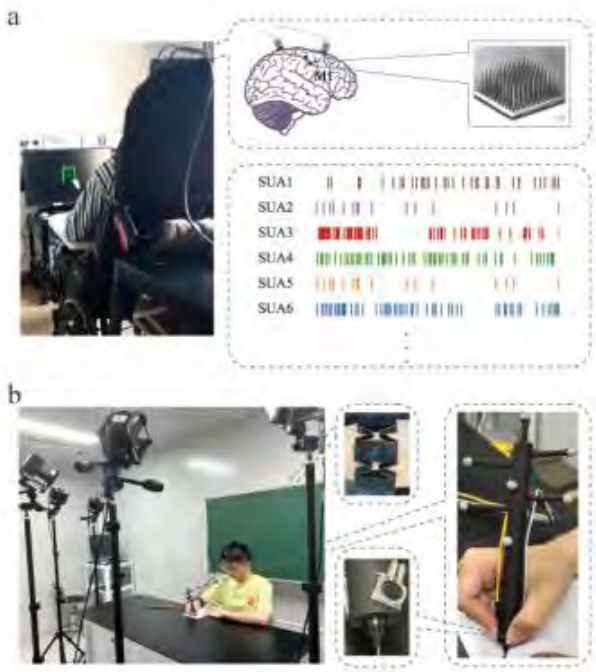

Figure 1: Experimental setup. (a), Two 96-channel Utah microelectrode arrays were implanted in the left M1 area of the paralyzed subject. The neural signal was recorded when he was imaging handwriting guided by a handwriting animation showed on the screen in front of him. (b), Multidimensional handwriting movements of a healthy subject were recorded during handwriting.

How NOKOV Contributes to the Research

A motion capture system,consisting of eight Mars4H lenses (NOKOV, China), was employed to track the trajectory of 7 markers affixed to the pen holder, from which we derived the velocity of pen tip. Additionally, we used4 thin-film pressure sensors (Leanstar, China) to document the grip force to the pen holder and pressure of the pen tip during handwriting.

Citation Wang Z, Xu G, Wang Y, et al. Neural encoding of multidimensional handwriting movements for brain-computer interfaces[C]//Proceedings of the 2024 11th International Conference on Biomedical and Bioinformatics Engineering. 2024: 104-109.

Link https://dl.acm.org/doi/10.1145/3707127.3707144

Neuromechanical Simulation of Human Postural Sway in the Sagittal Plane Based on a Hybrid Triple Inverted Pendulum Model and State-Dependent Intermittent Neural Control

Keywords

Neuromechanical modeling, human quiet stance, center of mass stabilization, intermittent control, natural postural sway

Abstract

Objective: This study introduces a novel neuromechanical model that employs a hybrid triple inverted pendulum (HTIP) framework combined with state-dependent intermittent control to simulate human quiet stance in the sagittal plane. Methods: The proposed neuromechanical model integrates the biomechanics of the ankle, knee, and hip joints, focusing on the stabilization of the body's center of mass (CoM) rather than controlling each joint individually. Unlike computational models that require precise joint control, the central nervous system maintains posture by simplifying neural control mechanisms. Specifically, the state-dependent control strategy activates neural feedback only as the CoM approaches the stability boundaries. Results: Experimental validation against real-world data demonstrated that the model can accurately replicate natural postural sway patterns in the sagittal plane. Conclusion: The model provides a computationally efficient mechanism and a realistic simulation of human posture control, addressing a long-standing challenge in neuromechanical modeling of human quiet stance. Significance: This study enhances understanding and simulation capability offers significant new insights for developing targeted interventions for individuals with impairments in postural control.

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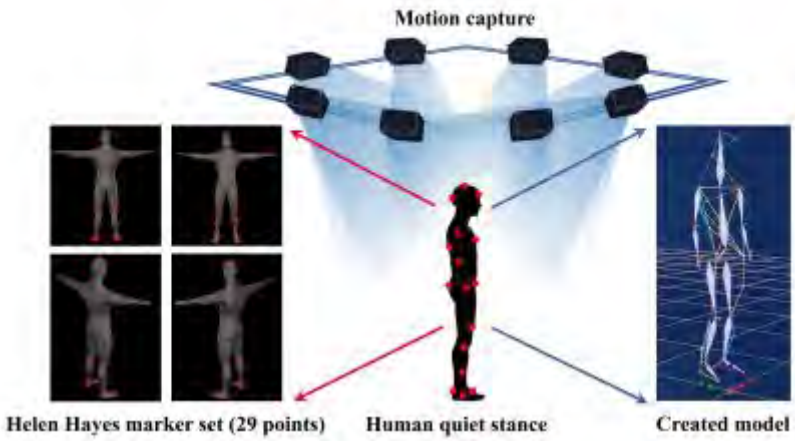

Fig. 6. The illustration of the experimental setup for capturing the dynamics of human standing in the sagittal plane using the Nokov 3D Optical Camera System and the Helen Hayes full-body with head marker set [49]. On the left side of the image, the Helen Hayes marker set is displayed, consisting of 29 points used to precisely track the motion of human joints and key body parts. Throughout the standing process, eight Nokov 3D Optical Cameras positioned above the subject's head record the posture in real-time. During this process, subjects were instructed to stand naturally, avoiding excessive focus or tension. Subjects' arms were to hang naturally by their sides, eyes open, with gaze directed straight ahead. On the right side of the image, the real-time human posture reconstruction is rendered using Nokov's Xingying 3.2 software.

How NOKOV Contributes to the Research

To accurately capture the dynamics of postural adjustments during quiet stance in the sagittalplane, this study utilized the Nokov 3D Optical Motion Capture System, as shown in Fig. 6. This system is capable of precisely tracking the human body in three-dimensional space and measuring corresponding motion parameters.

Citation Zhao Y, Zhang M, Hodossy B K, et al. Neuromechanical simulation of human postural sway in the sagittal plane based on a hybrid triple inverted pendulum model and state-dependent intermittent neural control[J]. IEEE Transactions on Biomedical Engineering, 2024.

Link https://ieeexplore.ieee.org/abstract/document/10758254

Non-human primate models and systems for gait and neurophysiological analysis

Keywords

non-human primate, gait, BCI, neurophysiological analysis, motor cortex

Abstract

Brain – computer interfaces (BCIs) have garnered extensive interest and become a groundbreaking technology to restore movement, tactile sense, and communication in patients. Prior to their use in human subjects, clinical BCIs require rigorous validation and verification (V\&V). Non-human primates (NHPs) are often considered the ultimate and widely used animal model for neuroscience studies, including BCIs V\&V, due to their proximity to humans. This literature review summarizes 94 NHP gait analysis studies until 1 June, 2022, including seven BCIoriented studies. Due to technological limitations, most of these studies used wired neural recordings to access electrophysiological data. However, wireless neural recording systems for NHPs enabled neuroscience research in humans, and many on NHP locomotion, while posing numerous technical challenges, such as signal quality, data throughout, working distance, size, and power constraint, that have yet to be overcome. Besides neurological data, motion capture (MoCap) systems are usually required in BCI and gait studies to capture locomotion kinematics. However, current studies have exclusively relied on image processing-based MoCap systems, which have insufficient accuracy (error: $\geq 4°$ and 9 mm). While the role of the motor cortex during locomotion is still unclear and worth further exploration, future BCI and gait studies require simultaneous, high-speed, accurate neurophysiological, and movement measures. Therefore, the infrared MoCap system which has high accuracy and speed, together with a high spatiotemporal resolution neural recording system, may expand the scope and improve the quality of the motor and neurophysiological analysis in NHPs.

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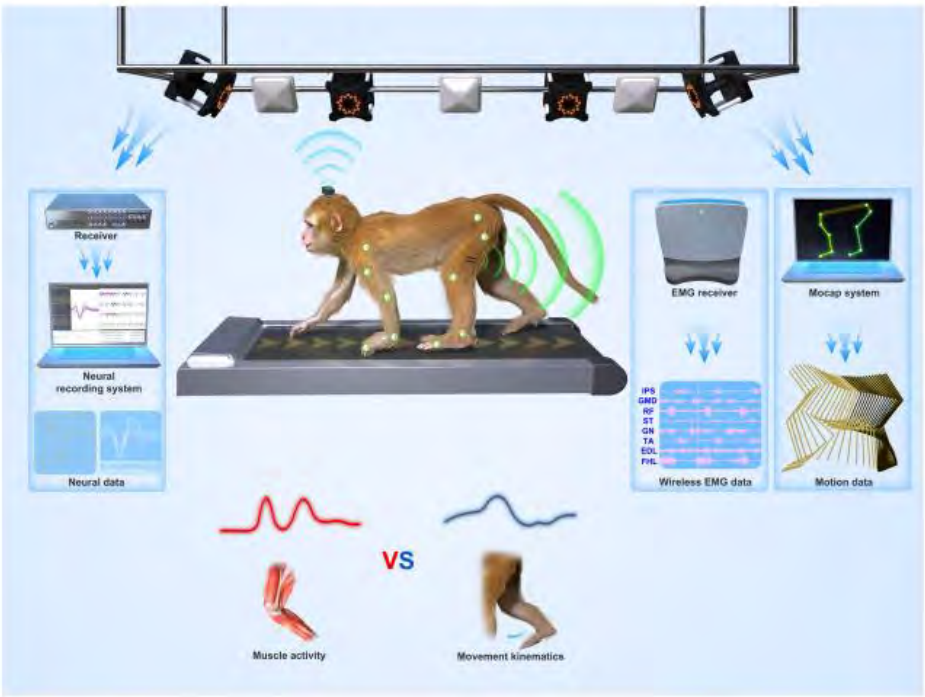

FIGURE 3
System overview of a suggested freely-moving (untethered) NHP model or paradigm. Wireless neural, EMG, and motion data from a monkey were recorded synchronously. The paradigm can be used to understand whether the motor cortex codes muscle activities (lower left panel) or movement parameters (lower right panel) during locomotion.

How NOKOV Contributes to the Research

Recently, our group is setting up an OS-based freely-moving NHP model (Figure3) with a high accuracy and fast speed MoCap system (Mars 4H, Nokov Science and Technology Co., Ltd., Beijing, China) along with a high spatiotemporal resolution neural recording system and wireless EMG system, to increase the accuracy of kinematics and thus expand motor and neurophysiological analysis in NHPs

Citation Liang F, Yu S, Pang S, et al. Non-human primate models and systems for gait and neurophysiological analysis[J]. Frontiers in Neuroscience, 2023, 17: 1141567.

Link https://www.frontiersin.org/articles/10.3389/fnins.2023.1141567/full

Optimizing toe joint stiffness to improve human-like walking

Keywords

Abstract

The human metatarsophalangeal joint often referred to as the "toe joint"-plays a vital role in gait by supporting body weight during mid-stance, enabling smooth rollover from heel to toe, and facilitating effective push-off in terminal stance. However, identifying its optimal stiffness remains challenging despite its relevance to both biological and robotic locomotion. In this study, we used a simulation-based trajectory optimization approach to investigate toe joint stiffness in a bipedal model. The results revealed that lower stiffness facilitated rollover while higher stiffness enhanced push-off. Because continuously varying stiffness is impractical in most passive devices, we extracted a single representative value (0.98 Nm/deg) by averaging the time-varying stiffness during the push-off phase. We then conducted a human walking experiment using adjustable toe joint boots across multiple stiffness conditions. The 0.98 Nm/deg condition yielded the highest subjective satisfaction and favorable spatiotemporal outcomes, especially among participants with anthropometry similar to the simulation model. Although direct numerical comparison between simulation and experiment was not performed due to modeling simplifications, key qualitative trends such as toe joint moment progression and heel-off timing were consistent. These findings highlight the potential of toe joint stiffness tuning to improve walking performance and user experience.

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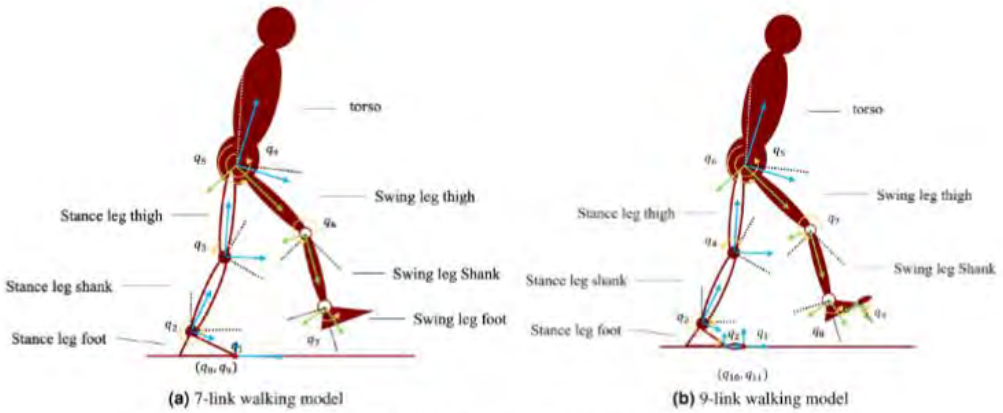

Figure 1. The schematics of the bipedal walking model for the simulation.

How NOKOV Contributes to the Research

Experiment methods
An experimental method was employed to evaluate the effect of the optimal toe joint stiffness. The average stiffness value during the push-off phase - where the toe joint plays the most significant role in the gait cycle - was calculated to validate the optimization results for the toe joint stiffness profile. This process yielded a passive toe joint stiffness value of 1.04 Nm/deg. A pair of simulated shoes with a passive toe joint was designed, as shown in Fig. 3. A cantilever spring made of 1095 spring steel was used to replicate the passive toe joint, with varying stiffness achieved by altering spring thickness. The overall length of each prosthetic foot was 28 cm from heel to toe, and the heel-to-MTP-axis distance was 20 cm, mirroring average human-foot anthropometrics reported in the literature [2]. These geometric constraints ensure that the adjustable toe joint operates about the same anatomical location and lever arm as the biological joint, thereby reproducing realistic joint kinematics and kinetics. The experimental setup included nine motion capture cameras (Nokov Mars, Beijing, China) and a 6-meter-long instrumented flat ground with a force plate (AMTI BMS400600-2000, MA, USA).

Citation Cho K, Lee K W, Hur P. Optimizing toe joint stiffness to improve human-like walking[J]. Scientific Reports, 2025, 15(1): 33268.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001582553800004

Perceiving visual events uses optical information that reflects dynamics rather than resembles appearance

Keywords

dynamics, events, point-light displays, viewing perspectives, visual kinaesthetic information

Abstract

This study investigates the optical information for visual event perception. Events are objects in motion, with properties like shape, weight and surface material influencing the dynamics that shape movements and optics. The progressive transformation of visible textures, known as visual kinaesthetic information, specifies movements and objects. Four experiments tested whether events could be perceived using only visual kinaesthetic information. Participants identified their own walking from point-light displays (Experiment 1), from simulated environmental texture transformations as a result of their walking (Experiment 2), and from videos shot by a head-mounted camera during outdoor walking (Experiment 3); and distinguishing strangers from footages captured by their head-mounted cameras (Experiment 4). In Experiments 2–4, the displays did not resemble the outline of a person or look like walking but revealed the physical relations between the walker and the environment as a result of their movement. Regardless, participants were able to recognize themselves and distinguish strangers. Thus, observers are able to perceive events using visual kinaesthetic information that stems from dynamics. The one-to-one correspondences between object property, dynamics, kinematics and optical information are governed by the laws of physics, and unaffected by the event's appearance or viewing perspectives.

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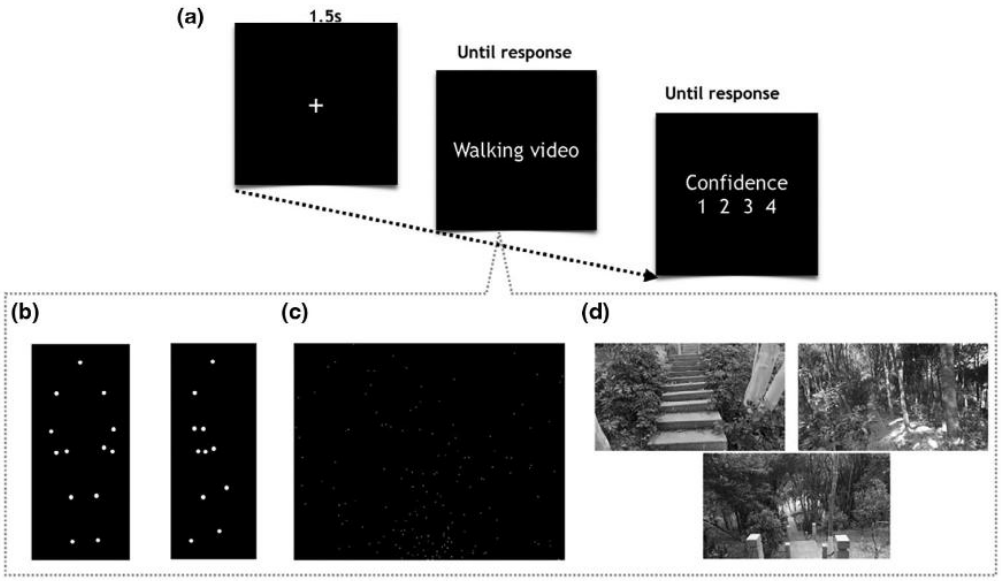

How NOKOV Contributes to the Research

This session was conducted in a 4.5 x9m room, the actual recording area was 4x8m, which could accommodate six complete gait cycles. Along the walls, 11 Nokov Mars 2H MoCap cameras (380 FPS sampling frequency) were positioned on tripods at 2.8 m above ground. The cameras tracked the 3Dpositions of reflective markers (diameter = 1.5 cm) with spatial errors <1.5 mm. The Commercial Seeker software (NOKOV Science and Technology Co., Ltd.; Version: 2.2) was used for marker reconstruction.labelling and trajectory interpolation during instances of data loss.

Citation Zhang H, Bingham G P, Pan J S. Perceiving visual events uses optical information that reflects dynamics rather than resembles appearance[J]. British Journal of Psychology, 2025, 116(1): 250-268.

Link https://onlinelibrary.wiley.com/doi/10.1111/bjop.12752

Personalized musculoskeletal model based multi-muscle force analysis for amputees with transtibial prostheses

Keywords

Multi-muscle force analysis, Musculoskeletal modeling, Transtibial amputee, Gait symmetry, Prosthetic optimization

Abstract

Understanding the biomechanical effects of transtibial prostheses is essential for their optimization and for improving amputee mobility. This study investigated how different prostheses impact intra-limb muscle coordination and inter-limb muscle force symmetry using personalized musculoskeletal models based on the sDIMS platform. Five transtibial amputees participated in gait trials with passive prostheses and active prostheses under varying damping conditions. The results were compared to those of five able-bodied controls. Through multi-muscle force analysis, we quantified muscle force magnitudes, identified coordination patterns, and evaluated inter-limb symmetry of multiple lower limb muscles using correlation coefficients, cyclograms, and symmetry indices. The results revealed distinct compensatory strategies in the intact limb based on group-level analysis. Furthermore, personalized evaluation based on multi-muscle force analysis enabled effective assessment of different prosthesis configurations in a subject-specific manner. These findings suggest that the proposed framework can improve prosthetic parameter selection and support the development of personalized control strategies, offering practical guidance for transtibial prosthesis optimization.

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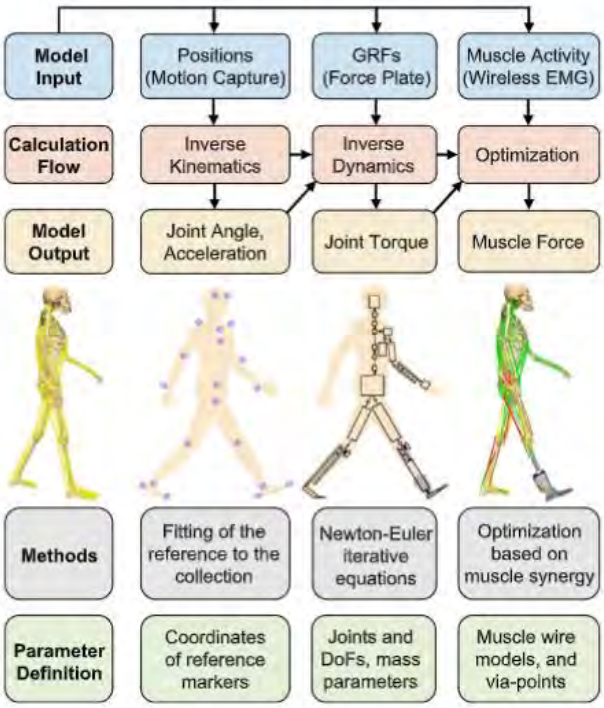

Fig. 1. Development of a full-body musculoskeletal simulation model for human movement in sDIMS.

How NOKOV Contributes to the Research

The experimental data included kinematics, ground reaction forces(GRFs), and electromyography (EMG)signals. All experiments wereconducted on a treadmill in a controlled laboratory environment, andparticipants were given time to adapt beforehand. The optical systemand treadmill force plates were calibrated before each trial. EMGsignal quality was ensured through standard skin preparation, includingshaving and cleaning. Kinematic data were collected using a 12-cameraoptical motion capture system (MARS4H, NOKOV, China) with a sam-pling frequency of 100 Hz, GRF data were recorded using a treadmillembedded with a force plate (Gaitway-3D 150/50, H/P/COSMOS, Germany)and EMG signals were recorded using a wireless EMG system(Delsys Trigno Wireless EMG System, Delsys, USA) with 16 channels,both at a sampling frequency of 1000 Hz.

Citation Lu Y, Huang Y, Jin W, et al. Personalized musculoskeletal model based multi-muscle force analysis for amputees with transtibial prostheses[J]. Journal of Biomechanics, 2025: 112913.

Link https://www.sciencedirect.com/science/article/abs/pii/S0021929025004257

Predictive Simulation of Human Body Bending Motion Based on Inverse Optimization

Abstract

Low-back pain (LBP) is the leading cause of disability in the world. Low waist exoskeleton devices have formed a new strategy to reduce the possibility of the LBP. Although most of the low waist exoskeletons have been developed, the candidate design of the device must be built and the control parameters must be manually adjusted based on trial-and-error, which may be a waste of human and material resources. Recently, human-in-the-loop approaches has been used to optimize motion tasks. This method is very promising in finding the best control parameters, and it is only used in relatively few parameters. When complex parameters need to be optimized, it may be difficult for the human-in-the-loop approaches to converge in a reasonable time. This makes the development of low waist exoskeleton device still challenging, in part because the current practice of establishing and testing cycle is time-consuming and laborious. To deal with the abovementioned challenge, this paper uses predictive simulation technology and OpenSim to study the control of human bending movement. Most of the existing researches give the weight of objective function in the form of manual adjustment, which is not scientific. Herein based on the idea of inverse optimization, by constructing a bi-level optimization framework, the problem of determining the cost function is transformed into a bi-level optimization problem. The experimental results show that the predictive simulation established in this thesis can reproduce the human autonomous bend motion. Thus, the proposed motion predictive simulation framework based on inverse optimization is feasible and effective, which can provide the theoretical basis and practical reference for realizing the predictive simulation of other complex human motions.

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How NOKOV Contributes to the Research

A total of six healthy male subjects (age= 23±3 years, mass = 61.25±6.25kg, height = 1.715±0.065m) voluntarily participated in and completed the bending experiment. This experiment contains a marker set of 39 Marker points, which is based on the detailed description of the marker set manual provided on the OpenSim official website. Placing markers on the corresponding key anatomical positions of the body. The overall process of the experiment is shown in Figure 2. Kinematics information is recorded through a passive optical motion capture system (Nokov, Beijing Metrology Technology Co., Ltd.). The force and moment information of the feet in three directions during bending movement was recorded by using the 6-dimensional force measuring platform (AMTI Company).

Citation Ba X, Zhou Y, Pang M, et al. Predictive Simulation of Human Body Bending Motion Based on Inverse Optimization[C]//2021 27th International Conference on Mechatronics and Machine Vision in Practice (M2VIP). IEEE, 2021: 109-114.

Link https://ieeexplore.ieee.org/abstract/document/9665102

Quantitative Assessment of Lower-limb Motor Function Based on Multimodal Gait Data for Hip Osteoarthritis

Keywords

Quantitative assessment, motor impairments, deep learning, multi-modal fusion

Abstract

The Harris Hip Score is very important in the clinical assessment of rehabilitation outcomes following Total Hip Arthroplasty (THA). Harris scales often have issues such as subjectivity and ceiling effects, it is difficult to measure the subtle changes in patients' disease progression. This paper proposes using deep learning algorithms to process multimodal gait data. First, conducting gait tests on THA patients to obtain optical motion capture data (MOC), surface electromyography data (sEMG), and force platform data (FP). Then, extracting features from these three modalities of data and input them into four models: LSTM, 1DCNN, 1DCNN-LSTM, and LSTM-1DCNN, to get the valuation results. Among these models, the 1DCNN-LSTM model performed best, with an L1Loss value of 9.952 and a correlation coefficient of 0.795 between the predicted values and the actual scores. This indicates that analyzing gait data with the 1DCNN-LSTM network can effectively predict Harris scores, which can provide a fundamental basis for the clinical diagnosis.

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How NOKOV Contributes to the Research

Data collection was performed using a NOKOV company-produced optical motion capture system equipped with eight infrared cameras to obtain the coordinate information of the markers on the patients' bodies. The frequency of the optical motion capture system was 200Hz.

Citation Tong L, Li Y, Wang C, et al. Quantitative Assessment of Lower-limb Motor Function Based on Multimodal Gait Data for Hip Osteoarthritis[C]//2024 IEEE International Conference on Advanced Information, Mechanical Engineering, Robotics and Automation (AIMERA). IEEE, 2024: 224-229.

Link https://ieeexplore.ieee.org/abstract/document/10735757

Research and First Application of 4D Radiation Dose Calculation in China

Keywords

4D dose, mesh phantom, motion capture, tetrahedralization, accurate protection

Abstract

Current techniques for calculating radiation doses can only provide 3D static dose distributions for upright individuals, falling short of meeting the demands for precise protection in the future. In pursuit of achieving 4D dose calculations, this study implemented polygonal-surface computational human phantoms deformations using three algorithms based on rigid body rotation matrix, volume Laplacian operators, and As-Rigid-As-Possible (ARAP) method. Subsequently, the research on motion-capture-guided phantom deformation was done. Utilizing the tetrahedral transformation technique based on the Delaunay algorithm, high-speed Monte Carlo calculation was achieved. The established methodology underwent first application in nuclear power plants, and the application results, specific to radiation work processes, validated the reliability and practicality of the proposed method. This breakthrough in key technological aspects of the 4D dose calculation method demonstrates its potential application in personnel precision protection during the operation and maintenance of nuclear facilities. The developed technology holds promise for advancing radiation protection in various scenarios within the nuclear industry.

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(a) THE NOKOV SYSTEM

How NOKOV Contributes to the Research

One set utilized products from Nokov Company (Figure 3(a)), consisting of 8 high-precision optical cameras, wearable reflective markers, and control software. This setup is suitable for precise capture under laboratory conditions. The reflective markers, characterized by high reflectivity, enable the cameras to determine the two-dimensional coordinates of each marker in their respective viewpoints.

Citation Liu Z, Zhao R, Liang R, et al. Research and First Application of 4D Radiation Dose Calculation in China[C]//International Conference on Nuclear Engineering. American Society of Mechanical Engineers, 2024, 88285: V008T09A027.

Link
https://asmedigitalcollection.asme.org/ICONE/proceedings/ICONE31/88285/V008T09A027/1208361?searchresult=1

Research on Athlete Injury Motion Capture Method Based on Multisource Sensing Signals

Keywords

Multisource sensing signals, Athletes, Capture of injury movements, Classifier

Abstract

The conventional athlete injury motion capture method mainly uses Orthoload optical capture standard calibration database to calculate the load on the injured joint, which is easily affected by the change of the sagittal plane coefficient of the contact moment, resulting in a high deviation of the knee flexion moment (KFM) of the injured joint. Therefore, a multisource sensing signal-based athlete injury motion capture method is proposed. By utilizing multisource sensing signals for adaptive detection of human posture domain, an athlete injury motion capture classifier was designed to achieve athlete injury motion capture. The experimental results show that the designed multisource sensing signal capture method for athlete injury movements captures the joint bending moment KFM of the injured joint and fits it with the actual joint bending moment KFM of the injured joint, which is reliable and has certain application value. It has made a certain contribution to reducing athlete sports risks and formulating reasonable repair plans.

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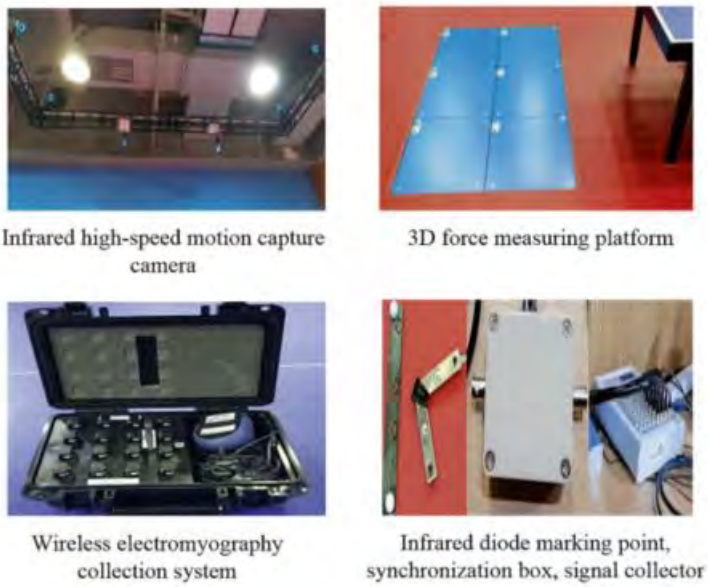

Fig. 4 Experimental instruments and equipment

How NOKOV Contributes to the Research

3.2 Experimental Results
Based on the above experimental preparation, the athlete injury motion capture experiment can be carried out, which involves collecting joint load data under different states, calculating the external force as the ground reaction force and external torque, initializing parameters, and setting different injury sites. The methods described in this chapter, reference \[2], and reference \[3l are used for motion capture. NOKOV is used to capture the motion capture delay and lateral capture deviation indicators of the three methods under different capture units, as shown in Table 1.

Citation Wang, L., Liu, H. (2025). Research on Athlete Injury Motion Capture Method Based on Multisource Sensing Signals. In: Zhang, Z., Wang, S. (eds) IoT and Big Data Technologies for Health Care. IoTCare 2024. EAI/Springer Innovations in Communication and Computing. Springer, Cham. https://doi.org/10.1007/978-3-031-90903-0_15

Link https://link.springer.com/chapter/10.1007/978-3-031-90903-0_15#citeas

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Research on Enhanced Gait Phase Segmentation Based on Multi-Modal Spatiotemporal Information Fusion

Keywords

Gait phase segmentation, inertial sensor, motion capture (MoCap), Multi-sensor data fusion, Graph Convolutional Network

Abstract

Gait phase segmentation, pivotal for understanding lower limb motion, finds applications in diverse fields like medicine and sports. While existing method often struggle with accuracy and adaptability in real-world settings, this study presents a novel methodology employing particle filters for precise lower limb motion capture (MoCap) utilizing inertial sensors, which can be used in more everyday environments and in a wider range of applications over a longer period of time. The innovative approach adeptly tracks walking movements, labeling six gait phases via skeleton reconstruction facilitated by the MoCap algorithm. Subsequently, we propose a neural network architecture amalgamating Temporal Convolutional Network (TCN), Graph Convolutional Network (GCN), and Long Short-Term Memory (LSTM). This architecture integrates raw data from inertial sensors with joint angles derived from reconstructed motion, achieving accurate segmentation of the six gait phases. Experimental validation compares the MoCap algorithm against an optical motion capture system, and the neural network's performance against state-of-the-art methods. Results demonstrate our method's superior accuracy of 96.94%, highlighting its efficacy in addressing gait phase segmentation challenges and propelling advancements in gait analysis.

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Fig. 10: Overview of IMU-MoCap validation experiment with comparison to Opt-MoCap.

How NOKOV Contributes to the Research

To validate our proposed IMU-based MoCap algorithm, an Opt-MoCap system, NOKOV, shown in Fig. 10, served as the golden standard to measure the accuracy of motion capture.

Citation H. Zhang, X. Liu, J. Li, J. Pan, C. K. Loo and A. Cangelos, "Research on Enhanced Gait Phase Segmentation Based on Multi-Modal Spatiotemporal Information Fusion," in IEEE Internet of Things Journal, doi: 10.1109/JIOT.2024.3502653.

Link https://ieeexplore.ieee.org/document/10758819

Robust adaptive PD-like control of lower limb rehabilitation robot based on human movement data

Keywords

Human movement data; Rehabilitation robot; Trajectory tracking; S-curve function; Similarity function

Abstract

The combination of biomedical engineering and robotics engineering brings hope of rehabilitation to patients with lower limb movement disorders caused by diseases of the central nervous system. For the comfort during passive training, anti-interference and the convergence speed of tracking the desired trajectory, this paper analyzes human body movement mechanism and proposes a robust adaptive PD-like control of the lower limb exoskeleton robot based on healthy human gait data. In the case of bounded error perturbation, MATLAB simulation verifies that the proposed method can ensure the global stability by introducing an S-curve function to make the design robust adaptive PD-like control. This control strategy allows the lower limb rehabilitation robot to track the human gait trajectory obtained through the motion capture system more quickly, and avoids excessive initial output torque. Finally, the angle similarity function is used to objectively evaluate the human body for wearing the robot comfortably.

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How NOKOV Contributes to the Research

Therefore, this paper adopts an nonlinear complex exoskeleton robot as the research object, and designs a robust adaptive PD-like control (RAPLC) based on real data. The schematic diagram of the principle is shown in Fig. 1. First, NOKOV three-dimensional (3D) infrared motion capture equipment and three-dimensional force measurement platform equipment are used to collect human gait movement data and plantar force data.

Citation Hu N, Wang A, Wu Y. Robust adaptive PD-like control of lower limb rehabilitation robot based on human movement data[J]. PeerJ Computer Science, 2021, 7: e394.

Link https://peerj.com/articles/cs-394/

Simulation of Human Posture Sway Based on Reference Control

Keywords

OpenSim, Musculoskeletal model, Reference control, Reference point trajectory

Abstract

Investigating human movement mechanism is meaningful since it can provide clues to controller designs of bionic robots. However, the complicated interactions between human neural and musculoskeletal cause this issue to be challenging. Fortunately, the reference control has recently shown its potential and reliability to deal with this issue. In order to evaluate the roles of this control mechanism in the simulation of human upright swing, this paper firstly builds a simulation platform of musculoskeletal model augmented with reference controller via leveraging OpenSim. Then, the muscle-driven simulations of anti-disturbance and intentional swing in sagittal plane are conducted by using the established platform. During this process, the parameters contained in the reference controller and the reference point trajectory in swing are optimized using the fminsearch optimizer. Lastly, the established platform is verified by computer simulation and experimental test. The results between comparison of the simulation results and experimental data confirm that the established method can simulate the actual human upright standing motion.

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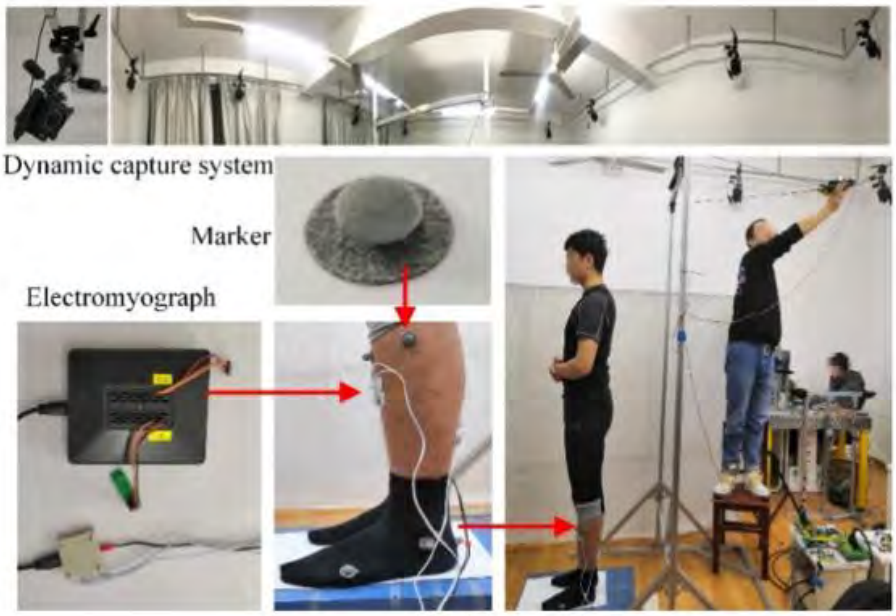

Fig. 3. Human upright anti-disturbance experiment

How NOKOV Contributes to the Research

The developed method is verified by comparing the simulation results obtained by our designed simulation platform with the experimental results. Prior to conducting experimental tests, a healthy volunteer without neuromusculoskeletal problems participate in two motor tasks in this study. The kinematics of the recruited volunteer are recorded in a Nokov optical three-dimensional motion capture system (Beijing NOKOV Science & Technology, 50 Hz) with eight high-definition cameras. Six reflective markers are placed on the medial and lateral shank and toes of the right leg to calculate the angle of the ankle. The muscle EMG signals of SOL and TA are measured by electromyography (ELONXI EMG 100-Ch-Y-RA). In the preparation of the experiment, the leg hairs of the subjects are removed and the skin is cleaned with alcohol. After that, EMG activity levels during maximal isometric voluntary contractions (MVC) are measured in standard muscle testing position for the subject before the experiment and used to normalize the EMG signals. The sampling frequencies of Nokov and EMG are 50 Hz and 1000 Hz, respectively. Moreover, we implement the real-time simulator to achieve the synchronous reception of experimental data.

Citation Zeng Q, Pang M, Tang B, et al. Simulation of Human Posture Sway Based on Reference Control[C]//International Conference on Intelligent Robotics and Applications. Cham: Springer International Publishing, 2021: 631-641.

Link https://link.springer.com/chapter/10.1007/978-3-030-89095-7_60

Space-time mapping relationships in sensorimotor communication during asymmetric joint action

Keywords

Sensorimotor communication, Asymmetric joint action, Message sender, Space-time mapping

Abstract

Background. Sensorimotor communication is frequently observed in complex joint actions and social interactions. However, it remains challenging to explore the cognitive foundations behind sensorimotor communication. Methods. The present study extends previous research by introducing a singleperson baseline condition and formulates two distinct categories of asymmetric joint action tasks: distance tasks and orientation tasks. This research investigates the action performance of 65 participants under various experimental conditions utilizing a 2 (cooperative intention: Coop, No-coop) × 2 (task characteristic: distance, orientation) × 4 (target: T1, T2, T3, T4) repeated-measures experimental design to investigate the cognitive mechanisms underlying sensorimotor communication between individuals. Results. The results showed that (1) target key dwell time, motion time, total motion time, and maximum motion height in the Coop condition are more than in the No-coop condition. (2) In the distance task without cooperative intention, the dwell time of T4 is smaller than T1, T2, T3, and its variability of T1, T2, T3, and T4 were no different. In the distance task with cooperative intention, the dwell time and its variability of T1, T2, T3, and T4 displayed an increasing trend. (3) In the orientation task without cooperative intention, the dwell time of T1 is smaller than T2, T3, T4, and variability of the target keys T1, T2, T3, and T4 had no difference. In the orientation task with cooperative intention, the dwell time and variability of the target keys T1, T2, T3, and T4 had increasing trends. Conclusions. Those findings underscore the importance of cooperative intention for sensorimotor communication. In the distance task with cooperative intention, message senders establish a mapping relationship characterized by ''near-small, farlarge'' between the task distance and the individual's action characteristics through sensorimotor experience. In the orientation task with cooperative intention, message senders combined sensorimotor experience and verbal metaphors to establish a mapping relationship between task orientation and action characteristics, following the sequence of ''left-up, right-up, left-down, right-down'' to transmit the message to others.

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How NOKOV Contributes to the Research

For motion tracking, a Nokov optical 3D motion capture system(Mars 4H, NoKov Corporation, Beijing, China) , manufactured by Beijing Nokov Science & Technology, was employed. A motion capture marker was affixed to the tip of the participant's right index finger, and seven high-power HLED luminaires (sampling rate=100 Hz) were used to capture the motion trajectory of the fingertip (marker).

Citation Zhang K, Tong X, Yang S, et al. Space-time mapping relationships in sensorimotor communication during asymmetric joint action[J]. PeerJ, 2024, 12: e16764.

Link https://peerj.com/articles/16764/

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The Application of Human–Computer Interaction Technology Fused With Artificial Intelligence in Sports Moving Target Detection Education for College Athlete

Keywords

artificial intelligence, framework of coaching system, motion capture technology, human-computer interaction, sports training

Abstract

The purposes are to digitalize and intellectualize current professional sports training and enrich the application scenarios of motion capture technology of moving targets based on artificial intelligence (AI) and human–computer interaction (HCI) in sports training. From an educational psychology perspective, sport techniques are a cognitive ability of sports, and a tacit knowledge. However, sports technology, language, image, and other methods play an auxiliary role in sports training. Here, a General Framework of Knowledge-Based Coaching System (KBCS) is proposed using the HCI technology and sports knowledge to accomplish autonomous and intelligent sports training. Then, the KBCS is applied to table tennis training. The athletic performance is evaluated quantitatively through the calculation of the sports features, motion recognition, and the hitting stage division in table tennis. Results demonstrate that the speed calculated by the position after mosaicking has better continuity after the initial frame of the unmarked segment is compared with the end frame of the market segment. The typical serve and return trajectories in three serving modes of slight-spin, top-spin, and back-spin, as well as the trajectories of common services and return errors, are obtained through the judgment of the serving and receiving of table tennis. Comparison results prove that the serving accuracy of slight-spin and back-spin is better than that of top-spin, and a lower serve speed has higher accuracy. Experimental results show that the level distribution of the three participants calculated by the system is consistent with the actual situation in terms of the quality of the ball returned and the standard of the motion, proving that the proposed KBCS and algorithm are useful in a small sample, thereby further improving the accuracy of pose restoration of athletes in sports training.

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How NOKOV Contributes to the Research

The running environment of the inertial capture system and optical capture system is the Window10 system. During the experiment, the computer CPU model is Intel i7-9700k, and the memory is 8G. The optical motion capture system is the Nokov, which can capture the key points of the trajectory at a higher frame rate. At the same time, the system has good stability and is suitable for the experimental requirements. The Legacy system is selected for inertial motion capture, which can output the posture of the main human bones more accurately. Meanwhile, the sensor of the Legacy system has a long life and can meet the application for a long time.

Citation Liu J, Wang L, Zhou H. The application of human–computer interaction technology fused with artificial intelligence in sports moving target detection education for college athlete[J]. Frontiers in Psychology, 2021, 12: 677590.

Link https://www.frontiersin.org/articles/10.3389/fpsyg.2021.677590/full

The influence of prior intention on joint action: An fNIRS-based hyperscanning study

Keywords

Prior intention; Joint action, Premotor and supplementary motor cortex, Temporo-parietal junction; Hyperscanning

Abstract

Motor performances of the same action are affected by prior intentions to move unintentionally, cooperatively or competitively. Here, a back-and-forth movement task combined with a motion capture system and functional near-infrared spectroscopy (fNIRS)-based hyperscanning technology was utilized to record both the behavioral and neural data of 18 dyads of participants acting in pairs \[joint conditions: no-intention, cooperative (Coop) and competitive (Comp)] or alone (single conditions: self-paced and fast-speed). The results revealed that Coop or Comp intentions in the joint conditions significantly sped up motor performance compared with similar single conditions, e.g. shorter movement times (MTs) in the Coop/Comp condition than the self-paced/fast-speed condition. Hemodynamic response analysis demonstrated that stronger activities for all joint conditions than the single conditions in the premotor and the supplementary motor cortex (Brodmann area 6) were independent of variations of MTs, indicating that they might reflect more complex aspects of action planning rather than simple execution-based processes. The comparisons of joint conditions across distinct prior intentions before acting yielded significant results for both behavioral and neural measures, with the highest activation of the temporo-parietal junction (TPJ) and the shortest MTs in the Comp condition considered to be implications for the top-down influence of prior intentions on joint performance.

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How NOKOV Contributes to the Research

A Nokov Optical 3D Motion Capture System(http\://www. nokov.com/en) was used to obtain movement data of two motion capture markers attached to the top of the rod at a sampling rate of 100 Hz, the coordination system was established at the calibration phase by putting a calibration tool at the experimental table. Movement data were preprocessed using Cortex 6.0 to acquire spatial coordinates for each marker, which includes the displacements of the markers in the x–y–z axes over time. And the x–y–z axes represent the vertical axis (x), the longitudinal axis (y) and the horizontal axis (z), respectly

Citation Chen Y, Zhang Q, Yuan S, et al. The influence of prior intention on joint action: an fNIRS-based hyperscanning study[J]. Social cognitive and affective neuroscience, 2020, 15(12): 1340-1349.

Link https://academic.oup.com/scan/article/15/12/1340/5995789?login=false

Updating of sensorimotor communication in an asymmetric alternating joint action task based on Real-time learning of interaction differences

Keywords

Alternating joint action, Feedback, Sensorimotor communication, Information sender

Abstract

Previous studies have suggested that sensorimotor communication promotes joint action. However, the studies were mixed with feedback factor. So the present study questions that result. The present study explores this question using two experiments based on asymmetric alternating joint action. Experiment 1 used a 2 (task: baseline, asymmetric alternating joint action) × 4 (target location: T1, T2, T3, T4) within-subjects design to examine the performance of asymmetrical alternating joint action with and without sensorimotor communication in 62 (30 males, 32 females) college students. It was found that, without feedback, the information sender increased the target key dwell time sequentially in the order of " up left, up right, down left, down right " to establish a sensorimotor communication pattern, which facilitated the achievement of asymmetric joint action. Experiment 2 used a 2 (task: baseline, asymmetric alternating joint action) × 2 (feedback: feedback, no-feedback) × 4 (target location: T1, T2, T3, T4) mixed design to further investigate the effect of feedback on asymmetric alternating joint action. Examined the asymmetric alternating joint action performance of 170 (84 male, 86 female) college students. The results indicate that sensorimotor communication and feedback jointly facilitate interpersonal motor coordination, feedback plays a key role. Specifically, without feedback, sensorimotor communication facilitates information transfer by establishing specific patterns based on sensorimotor experiences and verbal metaphors. With feedback, feedback facilitates information transfer by updating and optimizing sensorimotor communication patterns.

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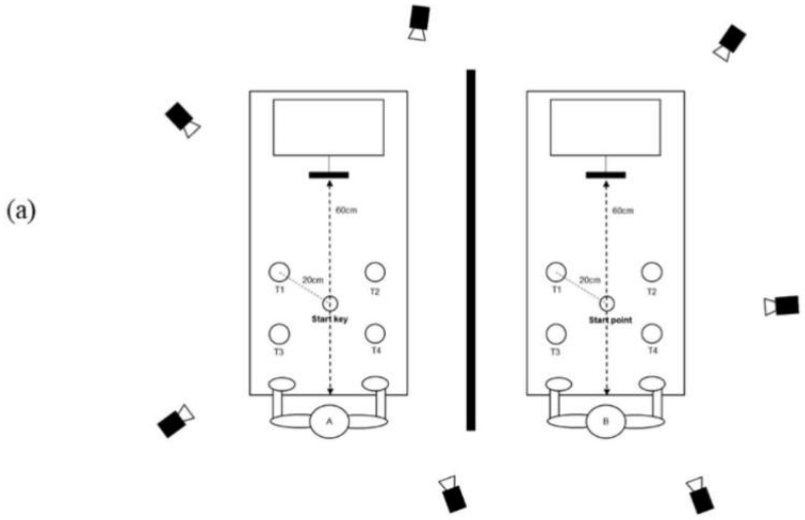

How NOKOV Contributes to the Research

Apparatus
Motion capture equipment was added based on Experiment1. Participants'fnger movements were recorded using the Nokov optical 3D motion capture system (Beijing Nokov Science & Technology Co., Ltd.). A reflective marker was fixed to the fingertip of the participants' right index finger,and the motion trajectories of the marker were captured using seven cameras (Mars4H). The sampling rate was set to 100 Hz.

Citation Tong X, Zhang K, Yang S, et al. Updating of sensorimotor communication in an asymmetric alternating joint action task based on Real-time learning of interaction differences[J]. Current Psychology, 2025: 1-18.

Link https://link.springer.com/article/10.1007/s12144-025-07640-2

Multimodal assessment of upper limb rehabilitation in stroke patients based on cross-attention mechanism

Keywords

Stroke, Multimodal data fusion, Rehabilitation assessment, Upper limb, Cross-attention mechanism

Abstract

Stroke, characterized by high incidence, disability, and mortality rates, often causes brain damage and upper limb impairment, making objective, efficient, and personalized rehabilitation assessment crucial. This study developed a multimodal system for assessing upper limb motor function in stroke patients. First, a markerless motion capture system using the Azure Kinect DK was developed and validated against a gold standard NOKOV Motion Capture, achieving high accuracy (joint angle MAE < 6°). Second, a multi-modal feature set integrating kinematics and electromyography (EMG) data was constructed based on a customized Short-FMA test protocol. Third, an improved Res-Transformer model was proposed, demonstrating superior efficiency (40% faster training) and higher accuracy (avg. 0.807 – 0.811 for single modalities) compared to Transformer, LSTM, and TCN. Finally, a multimodal fusion model (ReT-CA), integrating Res-Transformer with a cross-attention mechanism, achieved a high classification accuracy (average 0.892). This model formed the core of a digital assessment system, featuring clinical score prediction, visualization, and report generation. The system offers a low-cost, accurate solution for objective stroke rehabilitation assessment, with the potential to be widely adopted in communities, hospitals, and other use scenarios.

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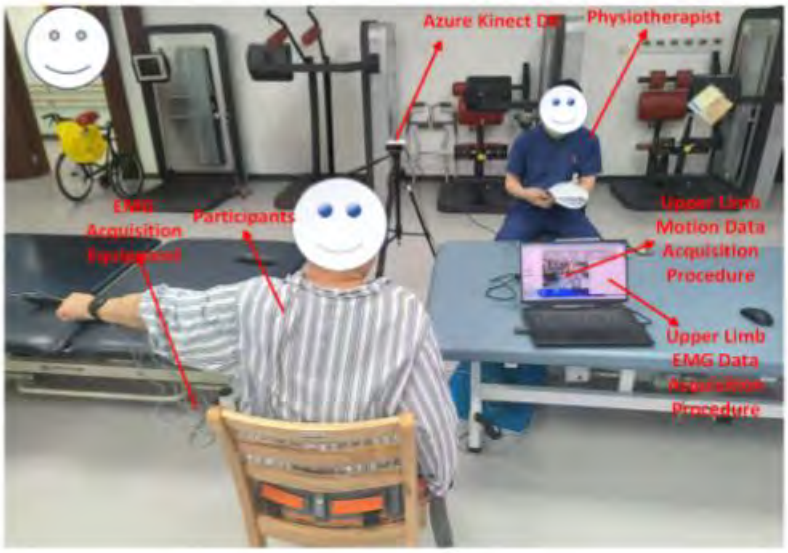

Fig. 18. Data collection environment.

How NOKOV Contributes to the Research

*Stroke, characterized by high incidence, disability, and mortality rates, often causes brain damage and upper limb impairment, making objective, efficient, and personalized rehabilitation assessment crucial. This study developed a multimodal system for assessing upper limb motor function in stroke patients. First, a markerless motion capture system using the Azure Kinect DK was developed and validated against a gold standard **NOKOV Motion Capture**, achieving high accuracy (joint angle MAE < 6°). Second, a multi-modal feature set integrating kinematics and electromyography (EMG) data was constructed based on a customized Short-FMA test protocol. Third, an improved Res-Transformer model was proposed, demonstrating superior efficiency (40% faster training) and higher accuracy (avg. 0.807–0.811 for single modalities) compared to Transformer, LSTM, and TCN. Finally, a multimodal fusion model (ReT-CA), integrating Res-Transformer with a cross-attention mechanism, achieved a high classification accuracy (average 0.892). This model formed the core of a digital assessment system, featuring clinical score prediction, visualization, and report generation. The system offers a low-cost, accurate solution for objective strokerehabilitation assessment, with the potential to be widely adopted in communities, hospitals, and other use scenarios.*

Citation Sheng B, Li S, Chen X, et al. Multimodal Assessment of Upper Limb Rehabilitation in Stroke Patients Based on Cross-Attention Mechanism[J]. Applied Soft Computing, 2026: 115199.

Link

https://ev.publinks.top/app/doc/?docid=cpx_M31a97ce319d8648a5c0M7af51017816360

A markerless Vision-Based 3D measurement system for postural risk assessment of stonemasonry workers using MotionBERT and REBA

Keywords

Construction Stoneworker, Computer Vision, Motion Capture, Ergonomics, HPE

Abstract

Work-related musculoskeletal disorders (WMSDs) remain a critical challenge in the construction industry, particularly within the stonemasonry sector characterized by high-load manual tasks and awkward postures. This study develops and validates a non-intrusive 3D human pose measurement framework, termed DLF-ERA, designed for automated ergonomic risk assessment in complex operational environments. To provide a robust metrological foundation, a high-fidelity 3D dataset (BSP3D) was established using an optical motion capture system, comprising over 50,000 frames across 15 typical stonemasonry activities. The proposed system utilizes a cascaded deep learning architecture: YOLOv8n for human detection, knowledge distillation-optimized RTMPose for 2D key points extraction, and MotionBERT for spatiotemporal 3D reconstruction. Furthermore, the system incorporates the Rapid Entire Body Assessment (REBA) method to evaluate the postural risk levels of stonemasonry workers. Experimental results demonstrate high precision in 3D posture estimation, with a Mean Per Joint Position Error (MPJPE) of 28.3 mm under obstructed field conditions. The automated risk classification achieved 86.2% accuracy compared to expert evaluations, confirming the system's reliability as a data-driven tool for field-based ergonomic monitoring. The findings suggest that the integration of spatiotemporal modeling and biomechanical coefficients significantly improves the robustness of vision-based measurements for occupational health management.

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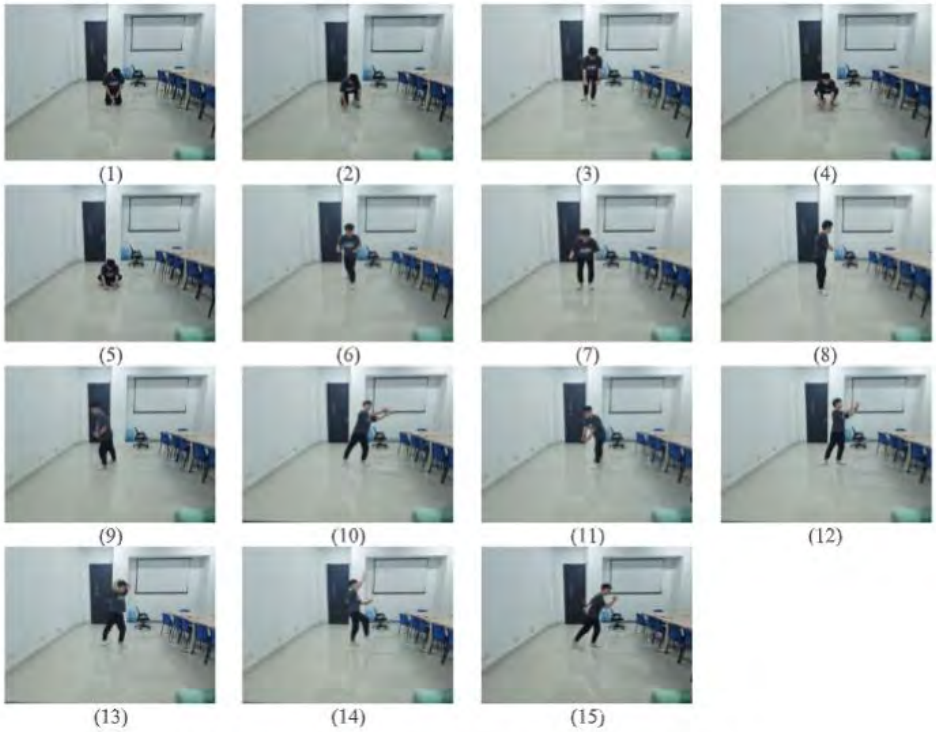

Fig. 2. Examples of the 15 most common construction stonemasonry worker activities.

How NOKOV Contributes to the Research

*This study employs a passive optical MoCap technology for 3D human position reconstruction. Grounded in computer vision principles, optical MoCap technology does its duty by deploying several high-speed cameras to synchronously track target feature points from various perspectives. The specific **NOKOV MoCap system** adopted for this research functions on the core idea of triangulation, reconstructing the accurate 3D spatial positions of passive reflective markers applied to the subject through geometric computing and data processing. The operation begins with many infrared (IR) cameras generating IR light into the capture region. High-reflectivity markers connected to the subject reflect this light back, appearing as high-luminosity pixels on each camera's image plane. Each camera captures the 2D pixel coordinates (μ,v) of these markers, and the system then performs a triangulation algorithm—using synchronous data from at least two cameras — to derive the 3D spatial coordinates (X, Y, Z) of each marker. These coordinates are recorded continuously at a predetermined sample rate to produce a high-fidelity motion trajectory.*

Citation Zheng Z, Wang C, Hu J. A markerless Vision-Based 3D measurement system for postural risk assessment of stonemasonry workers using MotionBERT and REBA[J]. Measurement, 2026: 121589.

Link https://www.sciencedirect.com/science/article/abs/pii/S0263224126012984

Exploration of an admittance control method for multi-segment spinal motion loading

Keywords

Multi-segment spine; Three-dimensional motion; Robotic arm; Range of motion; Admittance control

Abstract

Background: In vitro testing is a fundamental approach for advancing spinal biomechanics research. However, existing loading methods still exhibit notable limitations in physiological realism and motion controllability. This study introduces a spinal loading method that integrates robotic admittance control with dynamic movement primitives (DMPs) to enable motion loading of multi-segment spines, and provides a preliminary assessment of its reliability. Methods: A robotic testing system was developed, comprising a six-degree-of-freedom robotic arm integrated with a six-axis force sensor. Spinal traction trajectories were acquired with reference to anatomical planes, modeled, and subsequently reproduced using DMPs. The reconstructed trajectories were compared with the reference data to assess reproduction accuracy. The proposed method was further validated on ovine thoracolumbar specimens (T12-L3) under flexion-extension and lateral bending motions, and the measured ranges of motion (ROM) were compared with values reported in previous studies. Findings: A spinal loading method based on robotic admittance control combined with DMPs was successfully established. The experimental results demonstrated that the mean error between the demonstrated and reproduced trajectories was less than 2.5 mm, and the measured range of motion showed no significant difference compared with previously reported data ($P < 0.05$). Interpretation: The proposed method accurately reproduces physiological spinal motion characteristics, demonstrating its feasibility and validity for in vitro studies of three-dimensional spinal biomechanics.

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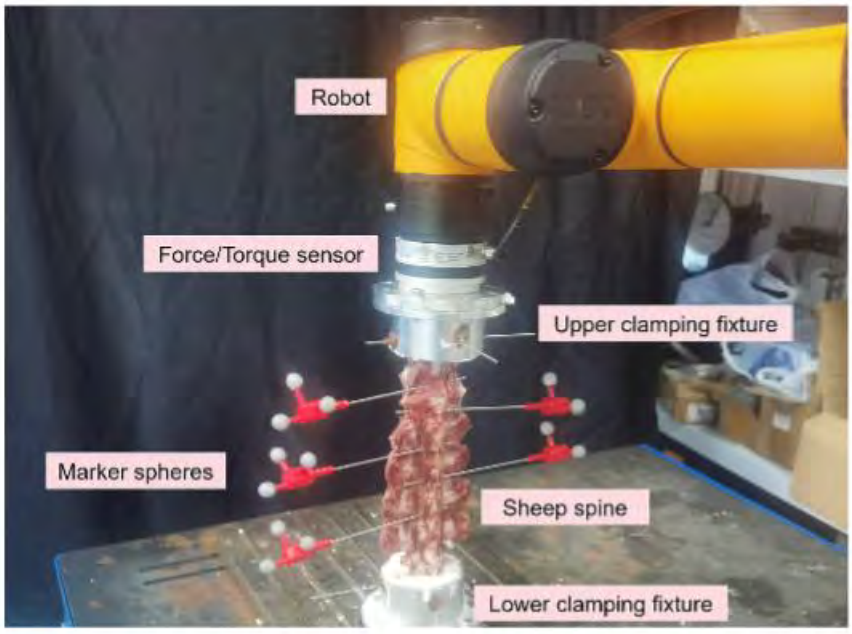

Fig. 3. Experiment setup.

How NOKOV Contributes to the Research

Four sets of trajectory data were used as demonstration inputs, from which the initial and target positions of the robotic arm end-effector were extracted and fed into the DMPs algorithm. Before trajectory reproduction, 3D-printed fixtures were mounted on the Kirschner wires of each vertebral segment, with three marker spheres attached to each fixture for tracking by the optical motion capture system (Fig. 3). In the main interface of the NOKOV optical motion capture system, noise filtering and environmental calibration were first performed on the captured images to ensure that only the reflective markers used for measurement remained within the system's field of view, thereby improving the accuracy and stability of subsequent motion data acquisition.

Citation Huang X, Ma Z, Cui X, et al. Exploration of an admittance control method for multi-segment spinal motion loading[J]. Clinical Biomechanics, 2026, 136: 106829.

Link https://www.webofscience.com/wos/alldb/full-record/WOS:001738407100001

Flexible kirigami microelectrode arrays for neuronal activity recordings in non-human primate brains

Abstract

The development of brain–computer interfaces requires implantable microelectrode arrays that can interface with numerous neurons across large spatial and temporal scales. However, creating arrays that can effectively accommodate the substantial movements and deformations of primate brains remains challenging. Here we report a kirigami-inspired flexible microelectrode array that has a reconfigurable spiral thread design and can be used for large-scale, long-term neuronal activity recordings in the primate brain. Each array can be transferred onto a hydrogel-coated brain surface using a water-dissolvable carrier, providing high-throughput delivery of multiple spiral threads across a large brain area. Stretchable spiral threads can be implanted into the cerebral cortex, with their base floating conformally on the brain surface to accommodate the large movements of the primate brain inside the skull. We show that the implanted array can provide simultaneous activity recordings from over 700 cortical neurons in a macaque monkey brain. We also demonstrate the accurate decoding of upper-limb kinematics from the spiking activity of the primary motor cortex (M1) neurons with a recurrent neural network model.

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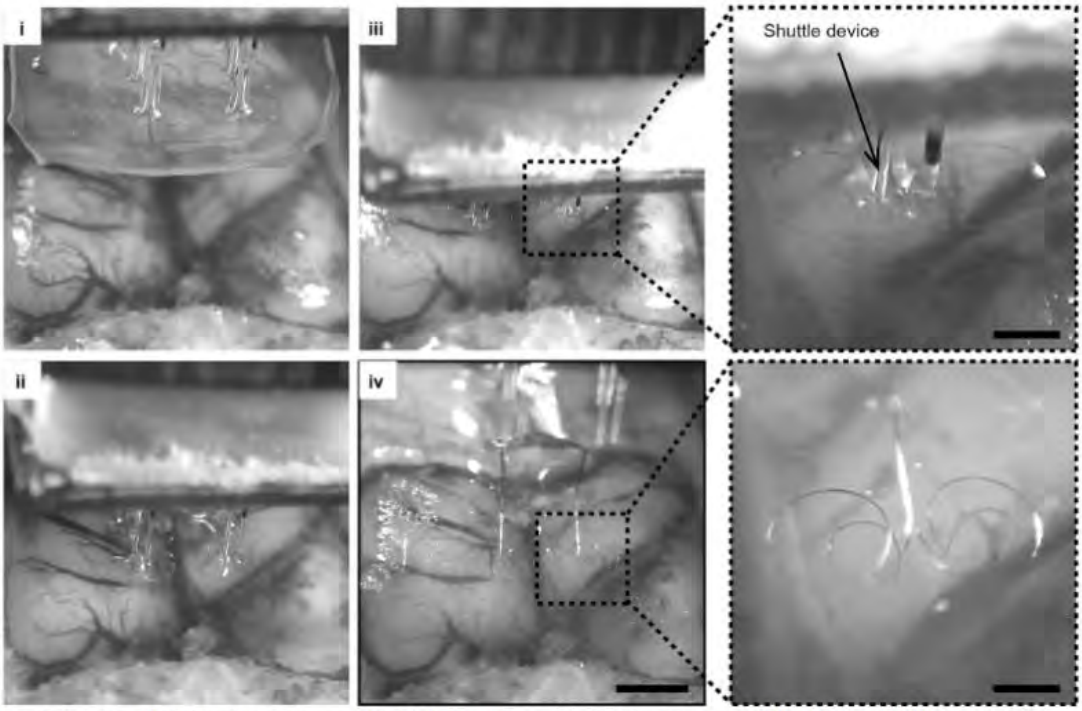

Extended Data Fig. 4 | High-throughput implantation of a *ki*-MEA. Time-series images showing the simultaneous implantation of a 4 × 3 spiral thread array into a rat brain, including SA/*ki*-MEA assembly transferring (i), PVA dissolution (ii), SA-assisted depth implantation (iii), and SA retraction (iv). Scale bars, 2 mm and 500 μm (enlarged views). High-throughput refers to the number of the flexible threads that can be implanted into the brain in parallel.

How NOKOV Contributes to the Research

The peripheral targets were spaced by 45° around the central point. Hand position was recorded at 60 Hz by a NOKOV motion capture instrument. During each trial, the monkey initiated the task by holding onto the central point for 200 ms. At target onset, one reach target appeared as white circles at one of eight radial locations. After a delay period of 200 ms, the go cue was initiated. The monkey needed to initiate the reach within 200 ms after the go cue, reach the peripheral target within 3 s and hold it for 200 ms. The monkey was rewarded with fruit juice after making a successful reach.

Citation Fang R, Tian H, Du Y, et al. Flexible kirigami microelectrode arrays for neuronal activity recordings in non-human primate brains[J]. Nature Electronics, 2026: 1-13.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001680635000001

FlexiScale: A Hybrid Marker-Based Scaling Method for Geometrically and Biomechanically Accurate Lower Limb Musculoskeletal Models

Keywords

inverse dynamics; joint contact force; marker-based scaling; muscle force; subject-specific musculoskeletal modeling

Abstract

Subject-specific musculoskeletal (MSK) models with individualized anthropometric features are essential for accurate biomechanical analysis, given the considerable anatomical and mechanical variability across individuals. Marker-based scaling provides a noninvasive, efficient, and cost-effective strategy for personalizing generic MSK models, yet its reliability and accuracy remain insufficiently validated. This study proposes a hybrid scaling approach (FlexiScale), which combines segment-wise linear scaling with global nonlinear morphing based on radial basis function (RBF) interpolation. This method enables simultaneous adjustment of relative segment orientations and overall skeletal geometry. To comprehensively evaluate its performance, two simpler baseline models were also constructed, including a uniform linear scaling model and a segmental linear scaling model. A reliability analysis was conducted by comparing knee joint contact forces predicted by the three scaling models with in vivo measurements obtained from an instrumented knee prosthesis under identical gait conditions. Furthermore, an accuracy validation was performed by comparing joint contact forces and muscle forces predicted by each scaling model against those derived from medical image–based subject-specific models across three daily activities (level walking, stair ascent, and stair descent) in both male and female subjects. Compared to conventional linear methods, FlexiScale consistently produced the most accurate and reliable geometric and biomechanical predictions across tasks and subjects. These findings demonstrate that the proposed hybrid approach can generate geometrically and biomechanically more accurate and robust MSK models than conventional linear scaling methods, even without medical imaging, thereby supporting subject-specific assessments and large-scale applications in clinical and research settings.

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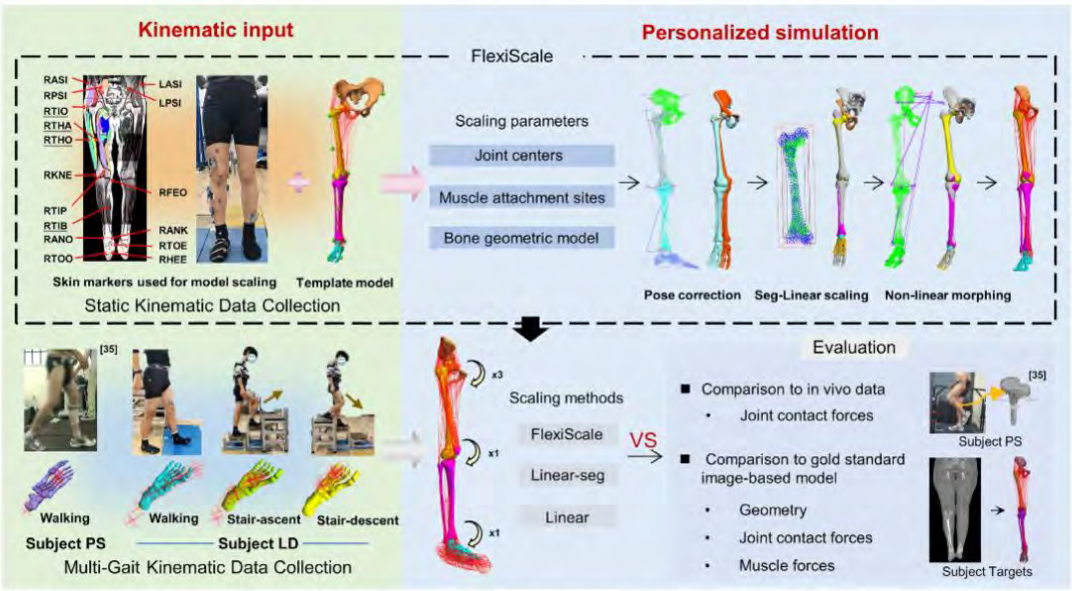

FIGURE 1 | Workflow for personalized MSK model construction and simulation. Skin markers were placed on the lower limbs at the anatomical locations illustrated in the figure (with nonbony landmark points underlined). Based on static marker data, the template model was scaled to each target subject using three approaches: FlexiScale, uniform linear scaling, and segmental linear scaling. Dynamic markers were then used to record body kinematics and ground reaction forces (GRF), together with center of pressure (COP) information. The reliability of the scaled models was first evaluated during level walking by comparing the predicted knee joint contact forces against in vivo measurements. Subsequently, taking the image-based target model as the reference, the geometric and dynamic accuracy of different scaling methods was assessed across level walking, stair ascent, and stair descent tasks. "Subject PS" shown in the figure corresponds to the participant from the Fifth Knee Grand Challenge dataset [33]. The video frame and prosthesis image are reproduced here for illustration of the data source only.

How NOKOV Contributes to the Research

In the absence of gait data for the TLEM2.0 and Visible Human subjects, gait data were collected from a healthy male subject LD (age: 24 years; height: 172cm; weight: 56kg) for use in simulation. Motion capture was performed using an infrared optical system (Mars26H, NOKOV, Beijing, China) and two force plates (BMS400600, AMTI, Watertown, USA), recording body kinematics and ground reaction forces during static standing, walking (mean speed: 1.17m/s), stair ascent (mean speed: 0.32m/s), and stair descent (mean speed: 0.35 m/s). All personal identifiers were removed to ensure the participant's anonymity.

Citation Xu J, Tang Z, Xia P, et al. F lexi S cale: A Hybrid Marker-Based Scaling Method for Geometrically and Biomechanically Accurate Lower Limb Musculoskeletal Models[J]. International Journal for Numerical Methods in Biomedical Engineering, 2026, 42(2): e70142

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001702921700006

Integrated Biomechanical Framework for Pathological Gait Analysis and Recognition via Multibody Dynamics and Enhanced Stability Metrics

Keywords

Pathological gait; Multibody dynamics; Multidimensional feature extraction; Margin of stability; Pattern recognition; Deep learning

Abstract

Accurate extraction of pathological gait characteristics and precise stability quantification remain critical challenges in recent biomechanical research, significantly limiting clinical capabilities in disorder diagnosis, fall risk assessment, and rehabilitation monitoring. This study addresses these limitations through an integrated biomechanical framework that synthesizes human multibody dynamics with enhanced Margin of Stability (MoS) metrics for multidimensional gait characterization. The human multibody system model captures complex biomechanical interactions and stability boundaries, and achieves high-precision identification of pathological gait. The methodology involves motion capture system acquisition of triaxial displacement/velocity profiles from 26 anatomical markers alongside ankle/knee joint angles, enabling development of multibody biomechanical models for center-of-mass trajectory computation. Comparative analysis of spatiotemporal parameters between normative and pathological gait patterns (idiopathic normal pressure hydrocephalus [iNPH], hemiplegia [HP], spinal cord injury [SCI]) facilitates discriminative feature extraction, supplemented by frequency-domain decomposition of joint kinematics through Fast Fourier Transform. Further, we developed four optimized MoS methods and benchmarked them against other stability criteria, including the conventional MoS, maximum Lyapunov exponent(LyE), and step-width specificity. The results proved that the refined MoS2 method is the most accurate for evaluating stability in pathological gaits. Finally, these biomechanical descriptors are integrated into a comprehensive feature set, and a pattern recognition framework is used to achieve robust classification of gait patterns, establishing a framework with clinical application value for gait analysis in the elderly population. This integrated framework provides quantitative tools for elucidating stability degradation mechanisms, offering a clinically translatable approach for diagnostic support and therapeutic outcome evaluation.

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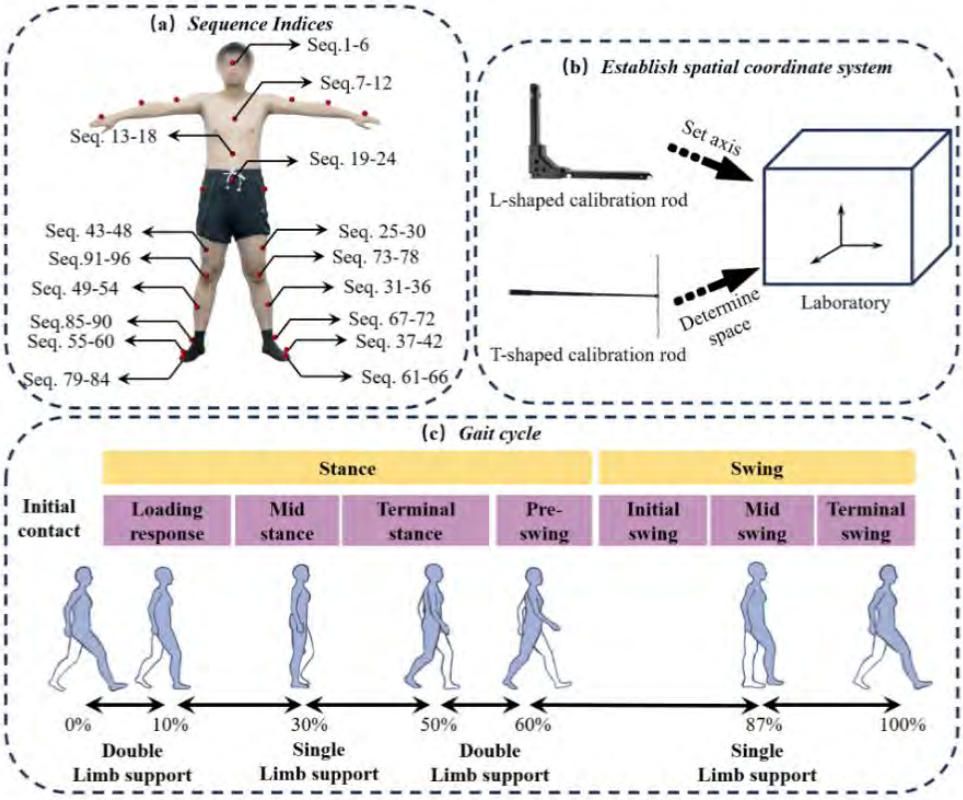

Fig. 2. Marker network and feature sequence analysis for gait kinematics. (a): Derived feature sequence indexes based on marker points, including positions and velocities along the X-, Y-, and Z-axes. (b): Established spatial coordinate system for data acquisition and preprocessing. (c): Distinct phases of the gait cycle and tests conducted based on this procedure to capture kinematic data.

How NOKOV Contributes to the Research

This laboratory employs a NOKOV motion capture system comprising 10 Mars4H cameras, a PoE switch, 15 mm reflective markers, and L/T-shaped calibration rods. These sensors precisely triangulate the three-dimensional coordinates and velocity vectors of markers through real-time detection of reflected infrared patterns, achieving positional accuracy within ±0.1 mm—a resolution that satisfies clinical-grade requirements for gait analysis. The integrated system's submillimeter tracking fidelity ensures reliable capture of subtle kinematic variations essential for biomechanical investigations.

Citation Pan Y, Chen W, Wang Z, et al. Integrated biomechanical framework for pathological gait analysis and recognition via multibody dynamics and enhanced stability metrics[J]. Pattern Recognition, 2026: 113553.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001732825400001

Real-Time Kinematic Reconstruction of Human Lower Limbs Using a 3-IMU Wearable Sensor Network, Transformer Model, and Deployable Edge Computing

Keywords

wearable sensors; inertial measurement unit (IMU); kinematic reconstruction; edge computing; human motion capture

Abstract

Continuous monitoring of lower-limb kinematics in natural environments is essential for gait analysis and rehabilitation but remains challenging due to the limitations of optical systems and the inaccuracy of sparse inertial sensor methods. To address this, we propose a high-precision, minimalist wearable system utilizing only three inertial measurement units placed on the pelvis and shanks. In the data preprocessing stage, engineering modifications are made based on the traditional gradient descent algorithm to implement adaptive channel adjustment on the acceleration and magnetic data of a single IMU, aiming to alleviate the impact of motion acceleration and external magnetic interference on the temporal feature manifold. Subsequently, a pure Transformer neural network is utilized to capture long-range temporal dependencies, reconstructing full lower-limb kinematics without relying on rigid biomechanical assumptions. The model was optimized and deployed on an STM32N647 microcontroller to achieve real-time edge inference with a low latency of approximately 17 ms. Experimental results demonstrate that the proposed method achieves a mean absolute error of 2.41 degrees for level walking, significantly outperforming traditional constrained Kalman filter approaches. Furthermore, it maintains high tracking robustness during complex nonlinear movements such as squatting and lunging. In conclusion, this edge-computing-enabled framework provides an accurate, comfortable, and real-time solution for unconstrained human motion capture in daily scenarios.

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Figure 3. Participant motion collection diagram.

How NOKOV Contributes to the Research

In terms of sensor placement, this study adopted a minimal 3-IMU layout ("pelvis + bilateral shanks"), as illustrated in Figure 2. The two shank sensors were firmly secured on the medial flat surfaces of both tibiae, where the subcutaneous tissue is relatively thin, effectively reducing vibration noise caused by muscle tremors during movement. The third sensor was fixed at the central posterior position of the pelvis, serving as a global reference for kinematic computation. The experiments were conducted in a laboratory equipped with the NOKOV Motion Capture System MARS2H (NOKOV Science and Technology Co., Ltd., Beijing, China), an 8-camera high-precision optical motion capture system, which was also set to a 100 Hz sampling rate.

Citation Yu Y, Dong W, Dong H, et al. Real-Time Kinematic Reconstruction of Human Lower Limbs Using a 3-IMU Wearable Sensor Network, Transformer Model, and Deployable Edge Computing[J]. Sensors, 2026, 26(12): 3706.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001803858300001

Adaptive Target-Crossing Zero-Velocity Detection Using Plantar Pressure Features

Keywords

zero-velocity detection; zero-velocity update; adaptive target-crossing; center of pressure; plantar pressure sensor

Abstract

Accurate detections of zero-velocity intervals (ZVI) are critical for foot-mounted inertial navigation systems, since the potential inertial drift errors can be suppressed through zero-velocity update (ZUPT) implementation. However, traditional threshold detection methods based on the inertial measurement unit (IMU) struggle to adapt to variations such as different walking speeds. Deep learning approaches impose high demands on embedded computational resources. To address these issues, this paper proposes an adaptive target-crossing (ATC) method based on the center of pressure (CoP) trajectory. The ATC method analyzes CoP trajectory variations from heel-strike to toe-off to adaptively determine the zero-velocity instant and the boundaries of the zero-velocity interval within the stance phase. An abruptness index and a velocity index are introduced and fused via a weighted mechanism to adjust the zero-velocity target position dynamically. To verify the performance of the proposed ATC method, it is compared with several popular methods using data from the motion capture platform as ground truth. Experimental results demonstrate that the zero-velocity detection rate of the ATC method reaches 98.9% while maintaining a low false alarm probability under mixed gait conditions (including walking, fast walking, and running) and incomplete gait scenarios. The proposed method outperforms several other widely used alternatives while maintaining a low false alarm probability.

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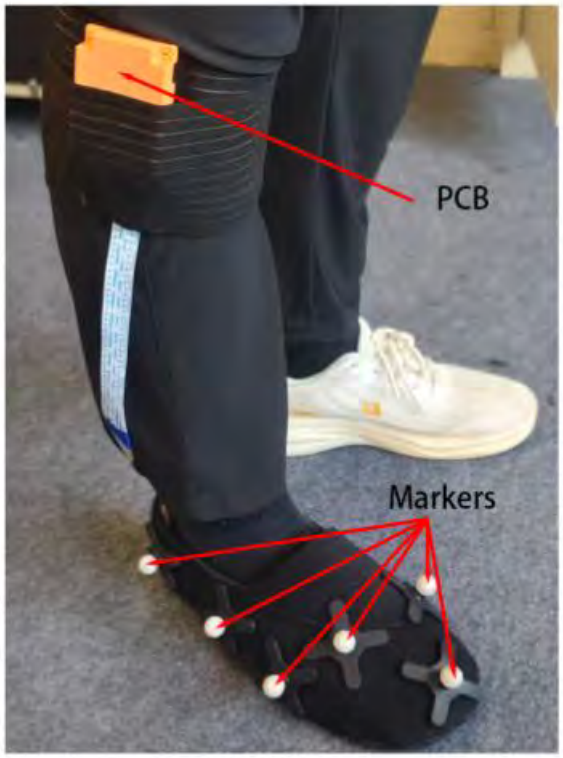

Fig. 1. ZVI detection system mounted on the foot.

How NOKOV Contributes to the Research

The experiments were conducted in a laboratory equipped with a NOKOV optical 3D motion capture system from Beijing Nokov Science & Technology Co., Ltd. The system consists of XINGYING software and 10 Mars series cameras. Fig.9(a) illustrates the motion capture frame and cameras mounted on the walls. Seven reflective markers were attached to the subject's shoe to construct a rigid body within the software, as shown in Fig.9(b) and Fig.9(c). The system calculates the 3D coordinates of the markers at a sampling rate of 125 Hz, calculates the three-axis velocity of the rigid body, and computes the resultant velocity. The experimental space measures approximately 8m×8m×3.7m, with a usable capture area of about 6m×6m. Due to the sufficient height margin, height restrictions are not considered.

Citation Zhang J, Xu X, Sun Y, et al. Adaptive target-crossing zero-velocity detection using plantar pressure features[J]. Measurement, 2026: 121865.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001790884400001

Evaluation of graft stiffness and material nonlinearity on knee biomechanics after ACL reconstruction using a dynamic finite element musculoskeletal model

Keywords

Knee biomechanics; Finite element musculoskeletal modeling; ACL reconstruction; Graft stiffness; Joint mechanics

Abstract

Background: Artificial ACL graft design often emphasizes replicating native nonlinear behavior; however, the relative biomechanical contributions of graft stiffness and toe-region nonlinearity under functional loading remain unclear, limiting guidance for graft selection and tensioning. Methods: A dynamically validated lower-limb finite element-musculoskeletal model simulated walking, stair ascent, and stand-to-sit activities. The model incorporated anatomically detailed 3D representations of ligaments, cartilage, menisci, and patellofemoral contact, driven by motion capture data. Artificial ACL grafts with stiffness levels of 75, 125, 175, and 300 N/mm were evaluated using linear and nonlinear material formulations, isolating toe-region nonlinearity under low-strain conditions. Results: Graft stiffness showed a stronger influence on knee biomechanics than material nonlinearity. Increasing stiffness elevated ACL forces and induced measurable changes in tibial rotation and contact center translation, while its effect on global joint loading remained limited. Differences between linear and nonlinear models were detectable only during low-load phases and remained small. Grafts within 75-175 N/mm produced consistent joint responses, whereas higher stiffness (300 N/mm) increased ACL stress and kinematic deviations. Conclusion: Within this computational framework and functional activities, graft stiffness plays a more influential role than toe-region nonlinearity. When stiffness is controlled, the contribution of toe-region nonlinearity appears limited under low-strain conditions. These findings represent mechanistic insights from modeling and require further experimental and clinical validation. (c) 2026 Elsevier B.V. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

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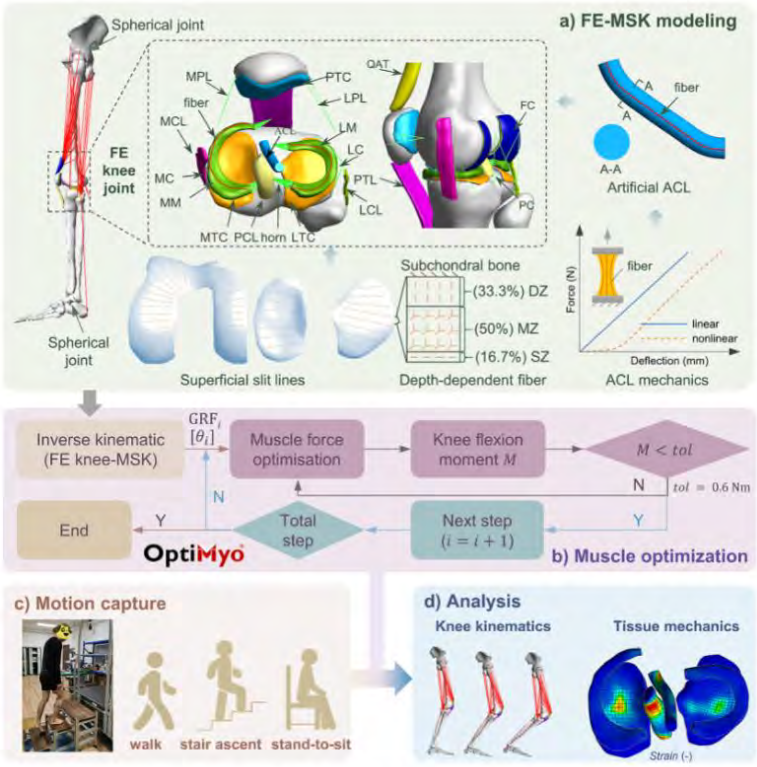

Figure 1. The workflow of this study. (a) FE-MSK modeling of the artificial ACL reconstruction. MTC/LTC: medial/lateral tibial cartilage; FC: femoral cartilage; PTC: patellar cartilage; QAT: quadriceps tendon, PTL: patellar ligament; MPL/LPL: medial/lateral patellofemoral ligament; MCL/LCL: medical/lateral collateral ligament; MC/LC/PC: medial/lateral/posterior capsule; MM/LM: medial/lateral meniscus. (b) Pipeline of the muscle force optimization. GRF_i represents the ground reaction force at moment i; $[\theta_i]$ is the rotational angle matrix of the three joints. (c) Motion captures experiment for walking, stair ascent, and stand-to-sit. (d) Kinematic and biomechanical analyses of the knee joint.

How NOKOV Contributes to the Research

A healthy male subject (23 years, 58 kg, 170 cm) with no history of knee injury or surgery performed three functional activities: level walking, stair ascent, and stand-to-sit. Kinematic data, ground reaction forces (GRFs), and surface electromyography (EMG) signals from the rectus femoris and gastrocnemius muscles were collected using a multi-camera motion capture system (Mars26H, NOKOV, China), force plates (BMS400600, AMTI, USA), and a wireless EMG system (Ultium, Noraxon, USA), respectively. Surface EMG data were used exclusively for qualitative validation of predicted muscle activation patterns and were not employed for direct force calibration. All experimental protocols were approved by the local ethics committee (SWJTU-2309-KJB (099)), and informed consent was obtained from the participant.

Citation Wang D, Hua X, Jin Z, et al. Evaluation of graft stiffness and material nonlinearity on knee biomechanics after ACL reconstruction using a dynamic finite element musculoskeletal model[J]. The Knee, 2026, 61: 104486.

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001765142000001

Effects of a 6-Week Hip and Ankle Mobility-Based Rehabilitation Program on Clinical, Neuromuscular, and Functional Outcomes in Male Collegiate Athletes with Patellofemoral Pain

Keywords

anterior knee pain; kinetic chain; exercise therapy; surface electromyography; dynamic balance

Abstract

Patellofemoral pain (PFP) in athletes is associated with lower-limb kinetic-chain constraints, yet rehabilitation strategies targeting both hip and ankle mobility remain insufficiently examined. This assessor-blinded randomized controlled trial investigated the effects of a 6-week hip and ankle mobility-based rehabilitation program in male collegiate athletes with PFP. Forty-eight participants were assigned using computer-generated 1:1 randomization to an intervention group (n = 24) or a control group (n = 24). The intervention group completed supervised hip and ankle mobility rehabilitation three times weekly, whereas the control group maintained regular sport-specific training only. Co-primary outcomes were pain intensity assessed using a 10-cm visual analog scale (VAS) and knee-related function assessed using the Kujala score. Secondary outcomes included hip rotation range of motion, weight-bearing ankle dorsiflexion, vastus medialis-vastus lateralis (VM-VL) onset timing, Y-Balance Test (YBT) composite score, and countermovement jump (CMJ) height. Significant group & times; time interactions favored the intervention group for VAS ($p < 0.0001$; partial eta(2) = 0.436; change difference: -1.54 cm; 95% CI: -2.06 to -1.02) and Kujala score ($p < 0.0001$; partial eta(2) = 0.285; change difference: 8.00 points; 95% CI: 4.24 to 11.76). Significant interactions were also observed for hip internal and external rotation range of motion, weight-bearing ankle dorsiflexion, VM-VL onset timing during a controlled squat task, and YBT composite score (all $p <= 0.0405$; partial eta(2) = 0.088-0.374). No significant group & times; time interaction was observed for CMJ height ($p = 0.0511$; partial eta(2) = 0.080). These findings suggest that, compared with regular sport-specific training alone, adding a supervised hip and ankle mobility-based rehabilitation program may improve pain, knee-related function, targeted mobility outcomes, VM-VL onset timing during a controlled squat task, and dynamic balance in the short term. However, because the control group did not receive an active or attention-

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matched intervention, these findings should be interpreted as the added effect of the supervised rehabilitation program rather than as definitive evidence of mobility-specific treatment effects. In addition, because patellar tracking, knee kinematics, joint kinetics, and patellofemoral joint loading were not directly measured, the findings should be interpreted as clinical and functional outcome changes rather than direct evidence of a confirmed biomechanical mechanism. Trial registration: NCT07542236.

Figure 4. Y-Balance Test assessment. Representative images of the anterior and posterolateral/posteromedial reaching tasks. YBT, Y-Balance Test.

How NOKOV Contributes to the Research

Vertical ground reaction force (vGRF) data were synchronously collected and exported using XINGYING Post Process software (version 4.4.0.6556; NOKOV Science & Technology Co., Ltd., Beijing, China) at a sampling frequency of 1000 Hz. Jump height was estimated using the take-off velocity method based on force-plate data.

Citation Xu H, Feng Z, Dou Y, et al. Effects of a 6-Week Hip and Ankle Mobility-Based Rehabilitation Program on Clinical, Neuromuscular, and Functional Outcomes in Male Collegiate Athletes with Patellofemoral Pain: A Randomized Controlled Trial[J]. Life, 2026, 16(

Link https://www.webofscience.com/wos/woscc/full-record/WOS:001805176500001

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Biomechanical Analysis of Hip Joint in Hemiplegic Patients Based on AnyBody Gait Simulation

Keywords

Gait Analysis · Circle Gait · Hip Joint · AnyBody Simulation

Abstract

In order to provide a biomechanical basis for the design of hip rehabilitation exoskeleton for stroke patients with hemiplegia, a comparative analysis of gait simulation was carried out. The motion capture system was used to collect the walking data of a healthy subject and a hemiplegic patient with typical circle gait. The biomechanical model was constructed based on AnyBody software. The differences of hip joint range of motion, angle, torque and key muscle activation characteristics between the two groups were compared and analyzed. The results showed that compared with healthy subjects, there were significant deviations in the biomechanical indexes of the affected hip joint in hemiplegic patients: the maximum flexion angle during the sagittal swing period was only 15.5°, with a decrease of 26.2%, and the flexion moment was seriously insufficient. The coronal plane showed compensatory abnormal abduction, and the maximum abduction angle increased by 66.3%. The peak values of the support phase adduction torque and the swing phase abduction torque increased significantly, and the end of the swing phase was accompanied by abnormal adduction. The activation sequence of the core muscle group is disordered, the early activation and muscle strength are significantly attenuated, and the late compensatory excessive activation is induced, which in turn induces the circular gait. Conclusion: By quantifying the above biomechanical deviations of the hip joint, the design requirements of the rehabilitation exoskeleton of the hemiplegic hip joint are clarified, which provides data support for the subsequent development and optimization of the exoskeleton.

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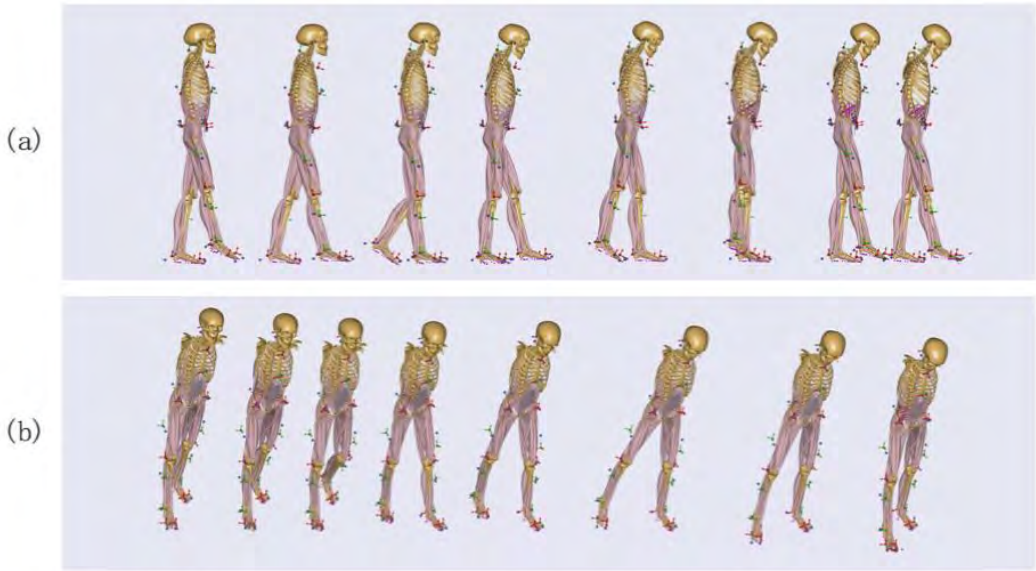

Fig. 4. Abnormal gait simulation results (a) side view (b) front view.

How NOKOV Contributes to the Research

2.2 Data Acquisition Experiment\n\nThe NOKOV optical motion capture system (sampling frequency 90 Hz) was used to collect gait data of the subjects. According to the model in anybody software, 22 reflective marker points (8 upper limbs and 14 lower limbs) are pasted, as shown in Fig. 1. The subjects walked on a flat walking channel at a speed that they thought was comfortable. Healthy subjects completed 3 effective tests (about 7 s each time, including 3 gait cycles). Hemiplegic patients completed 3 effective tests (about 10 s each time, including 3 gait cycles). Each test interval was 1–2 min to avoid fatigue.

Citation Liu H, Wang X. Biomechanical Analysis of Hip Joint in Hemiplegic Patients Based on AnyBody Gait Simulation[C]//International Conference on Human-Computer Interaction. Cham: Springer Nature Switzerland, 2026: 262-270.

Link https://link.springer.com/chapter/10.1007/978-3-032-30833-7_28

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“对角线”式对抗法对大学生伦巴舞动态平衡能力影响的实验研究

关键词

生物力学；伦巴舞；动态平衡能力；对角线式对抗

摘要

【目的】研究“对角线”式对抗法在完成伦巴舞动作过程中的动态平衡能力，从而提高拉丁舞选手在专项技术动作中的完成质量，提高动作精确性及更好的控制身体的动态平衡获得最佳的运动效果为研究目的。

【方法】本文采用的研究方法有文献资料法，专家访谈法、数理统计法、对比分析法，实验法。选取广州体育学院体育舞蹈方向主攻拉丁舞 12 名体育舞蹈专项和非体育舞蹈专项 12 名学生(共计 24 人)作为本次实验对象。他们在健康体检，身体素质各项指标正常，训练年限处在 3-6 年，年龄无显著性差异。实验组及对照组中专项组和业余组人数均为 3 人，男女比例 1:1。实验组采取“对角线”式对抗法和对照组采取传统训练方法进行 8 周训练。对实验组和对照组采集干预前、干预后的相关数据进行比较，运用 SPSS21.0 软件对数据进行配对 T 检验和独立样本 T 检验分析及运用 EXCEL 软件对数据进行极值、标准差等综合评价。

【结果】两组进行干预后通过两个独立样本 T 检验进行比较 Z 轴重心高度差异比较动态平衡。相比干预前，实验组干预后在 Z 轴重心高度的均值和标准差及方差均比对照组干预后小，证明离散程度小，呈密集。

【结论】（1）对照组采取传统教学方法进行干预，实验组采取“对角线”式对抗法进行干预，通过 Z 轴重心高度进行比较。实验组干预结果优于对照组干预结果。（2）通过“对角线”式对抗法提高了动态平衡能力，提高了对肩关节、肩胛骨、胸椎、髋关节、膝关节、踝关节及大腿内侧的控制和柔韧素质的开发及控腿能力，提升了舞蹈技术水平的同时提高学生分析能力，引导和启发学生重视知识技能储备，理解伦巴舞在运动过程中上下半身的对抗与平衡关系。（3）“对角线”式的首要点控制肩关节防止角度变化。其次前胸和肩胛骨、胸椎及髋骨维持平面是教学法完成的重要环节，两侧肩关节的差值越接近于 0 值越平衡，最后关键身体部位维持在特定的角度活动范围。

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③被试者完成实验数据采集后，操作人员对动态捕捉软件（NOKOV）的被试者人员数据进行运动学数据处理和分析。每一位被试者的过程相同，在此不给予详细介绍。④实验完成后，被试着保持安静状态下自行离开实验室，实验操作者逐个检查动态捕捉实验数据是否存在记录完整，尔后将每个被试者的文件名以"干预前/后+组别+号数+专业/业余组+性别"的方式进行截取整理，最终拷贝及保存测评数据。

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4D 人体辐射剂量计算技术研究

关键词

4D 剂量；面元模型；动作捕捉；四面体切割；精准防护

摘要

当前人体辐射剂量计算技术只能给出直立人体 3D 静态剂量结果，无法满足未来精准防护需求。为实现 4D 剂量计算，首先基于刚体旋转矩阵、体积图拉普拉斯算子和近似刚体变换三种算法实现了面元模型变形；然后研究了动作捕捉引导的模型变形；接下来基于 Delaunay 算法的四面体切割技术实现了高速蒙特卡罗计算，最后设计开发了 4D 剂量计算应用系统。将建立的完整方法用于核电厂进行现场实验，针对特定辐射作业过程的应用结果验证了该方法的可靠性和实用性，突破了 4D 剂量计算过程中关键技术环节。未来该技术有望在核电厂运维、核设施退役治理及医学介入治疗等场景下实现人员精准防护。

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借助动作捕捉设备捕获人体完整的时序性姿态，然后引导面元模型进行相应姿态调整，以高准确性在剂量模拟计算中重现人体实际动作情景，达到 4D 剂量计算目的。本文使用了两套光学动作捕捉系统：一套采用 NOKOV 公司产品（图 3（a）），由 8 个高精度光学摄像头、可穿戴反光球（Marker）与控制软件组成，适用于实验室条件下的精准捕捉，反光球具有高反光率，可将可见光反射回摄像头，以此确定每个摄像头视角下反光球的二维坐标，利用控制软件结合摄像头位置重建后可得到各反光球的三维坐标，可穿戴反光球固定在动作捕捉模特人体上的位置称为参考点，软件可以准确记录参考点三维位置的时间序列，据此建立动作捕捉骨架姿态的时间序列。

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BOSU 球训练对体育院校网球专选班男生平衡能力影响的实验研究 ——以广州体育学院为例

关键词

BOSU 球；体育院校；网球专选班；平衡能力

摘要

随着网球运动的不断发展，人们在关注网球技术的同时也注意到了身体素质训练对网球技术的影响，而平衡能力作为身体素质的重要组成部分，是运动技术上不可或缺的要素之一。近年来，平衡能力训练越来越得到人们的重视，逐渐应用到竞技体育或者体育院校的训练中去。本文通过参考 EvertVerhagen 训练，在结合网球专项特点的基础上，设计了渐进式的 BOSU 球平衡能力训练。旨在丰富体育院校网球专选班的教学手段，最终达到提高体育院校网球专选班男生的网球技术水平，也为其他相关领域的研究提供一定的理论参考。本文主要采用文献资料法、实验法，数理统计法等，以广州体育学院 2018 级网球专选班男生为实验对象（1 年以上的网球球龄，且都是右手持拍），随机分为实验组和对照组，每组各 7 人。实验前对实验组和对照组男生进行身体形态测试、平衡能力测试、网球基本技术测试和网球正反手击球技术动作分析，实验后对实验组和对照组男生同样进行身体形态测试、平衡能力测试、网球基本技术测试和网球正反手击球技术动作，得出以下结论：实验前，实验组和对照组学生在基本身体形态、平衡能力、网球基本技术和网球正反手击球技术动作没有显著性差异，可以进行下一步实验。实验后得出，实验组学生在 BOSU 球上进行平衡能力训练的效果好于对照组学生。具体表现在以下几个方面：（1）在平衡能力上，BOSU 球训练对于提高实验组学生静态平衡能力、动态平衡能力有显著效果，对重心控制能力和平衡能力都有提高。对照组学生的平衡能力也有提高，但效果不如实验组。（2）在网球基本技术上，本论文网球基本技术测试采用的是 ITN 网球等级测试系统，BOSU 球训练对实验组学生的正反手击球深度得分、正反手击球准确性得分和专项移动能力得分有显著性效果，得分高于实验前，提升的幅度大于对照组学生。（3）在正反手网球击球动作技术上，BOSU 球训练在缩短实验组学生移动 4 米正反手击球技术动作缓冲阶段的时间，降低最大缓冲瞬间的重心合速度和重心高度有显著性差异；对缩短实验组学生移动 4 米正反手击球技术动作蹬伸阶段的时间，降低最大蹬伸瞬间的重心合速度和提高蹬伸阶段的重心高度有显著差异。对照组学生的训练效果不如实验组。（4）BOSU 球训练在体育院校网球专选班男生的平衡能力训练中效果显著，并且以其高效、形式多变、富有挑战性等特点，增加了训练趣味性的同时也使得 BOSU 球训练在课堂上有较高的认可度。

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图 1 Nokov-Mars 2H 三维动作系统配件

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（ 4）运动生物力学测试仪器：本文采用的是 Nokov-Mars2H 三维动作捕捉系统，对 14 名实验对象正反手移动击球的技术动作进行运动学数据采集，采集的频率为 200 帧/秒。 Nokov-Mars2H 三维动作捕捉测试系统如图 1 所示，此系统采用光学反射原理捕捉信号源，实时记录动点的运动轨迹。本文根据研究的需要，通过三维动作捕捉系统采集测试者重心合速度、重心高度等运动学参数，测试现场如图 2 所示。

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ERB 辅助练习对羽毛球初学者训练中专项步法的影响

关键词

羽毛球初学者；步法练习；ERB

摘要

研究目的：ERB 辅助练习在训练时与人体关节运动时所产生的力量曲线非常相似。其所提供的阻力可以不受自身重力的影响，模仿各种身体活动，在不同平面上进行训练。因此，本研究根据羽毛球运动的项目特征和专项步法的技术特点，探讨 ERB 辅助练习对羽毛球初学者专项步法的影响。研究方法：本文采用文献资料法、专家访谈法、教学实验法、运动学研究方法、数理统计法和对比分析法等。以 ERB 为辅助练习器械，对未经过专业训练的广州体育学院 19 级体育教育专业羽毛球选修 1 班（10 名）为对照组采用常规训练、2 班(10 名)为实验组进行为期 12 周的 ERB 辅助练习。选取立定跳远、纵跳摸高、30 米跑、交叉灵敏性测试指标评价羽毛球初学者下肢力量、爆发力和灵敏性。选取五次前后进退跑、五次左右摸边跑、十次低重心场地四角跑评价羽毛球初学者专项步法移动能力。选取羽毛球专项步法取位阶段、移位阶段、击球缓冲阶段、蹬伸回动阶段的重心合速度等运动学指标对羽毛球初学者专项步法的技术特点进行评价。

研究结果：（1）实验后，实验组立定跳远、纵跳摸高、右脚支撑灵敏性与对照组相比有显著性提高（$p<0.05$），30 米跑与对照组相比提升幅度具有非常显著性（$p<0.01$）。（2）实验后，实验组五次直线进退跑、五次左右摸边跑、十次低重心场地四角跑与对照组相比提升幅度具有显著性（$p<0.05$）。（3）实验后，实验组取位阶段的重心合速度测试均值从大到小依次为：右前场 2.42m/s、左后场 2.32m/s、左前场 2.11m/s、右后场 1.77m/s，与对照组相比右前场与右后场重心合速度的提高具有显著性（$p<0.05$）。（4）实验后，移位阶段实验组前场与后场重心合速度显著提高，对照组右前场、左前场、左后场重心合速度显著提高。实验组移位阶段的重心合速度测试均值从大到小依次为：右前场 2.69m/s、左后场 2.43m/s、左前场 2.41m/s、右后场 2.26m/s，与对照组相比右前场重心合速度的提高具有显著性（$p<0.05$）。（5）实验后，实验组击球缓冲阶段右前场、左前场重心合速度降低幅度具有显著性（$p<0.05$），右后场重心合速度提高幅度具有显著性（$p<0.05$）。对照组右前场重心合速度降低幅度具有显著性（$p<0.05$）。其中实验组前场的重心合速度测试均值分别为：右前场 0.9m/s、左前场 0.99m/s，且实验组与对照组相比，右前场、左前场重心合速度降低的幅度具有显著性（$p<0.05$）。（6）实验后，实验组与对照组右前场、左前场蹬伸回动阶段重心合速度的提高具有显著性（$p<0.05$），右后场蹬伸回动阶段重心合速度具有显著性降低（$p<0.05$）。对照组实验后右前场蹬伸回动阶段提高幅度具有显著性（$p<0.05$），左前场蹬伸回动阶段具有非常显著性提高（$p<0.01$）。其中实验组右前场与左前场蹬伸阶段的重心合速度分别为：右前场 2.19m/s、左前场 1.97m/s，与对照组相比左前场重心合速度的提高具有显著性（$p<0.05$）。

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研究结论：（1）通过 ERB 辅助练习可以提升羽毛球初学者的专项步法移动能力，促进下肢力量、爆发力在人体关节链中输出的效率，提高初学者专项步法移动时的快速反应、变向与移动能力。（2）通过 ERB 辅助练习可以促进羽毛球初学者在专项步法的移位阶段抢到更有利的击球点与击球位置。提高初学者前场专项步法击球缓冲阶段的制动缓冲能力与击球后回位意识。

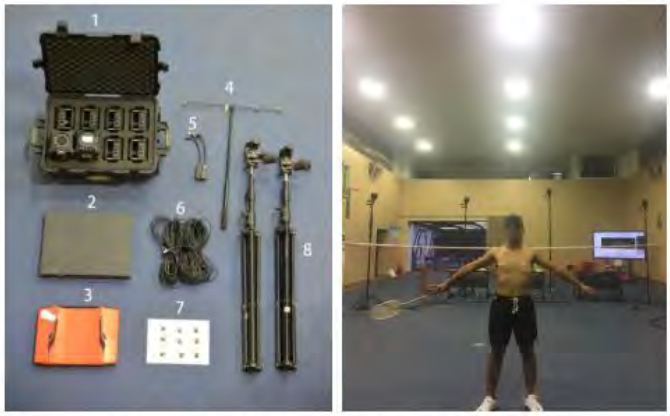

图 3-1 三维动作捕捉系统相关设备与受试者测试现场

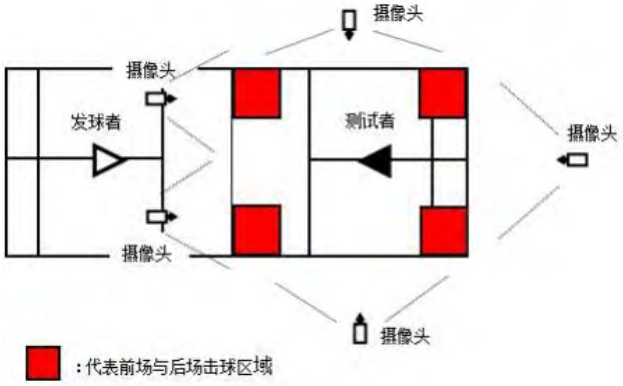

图 3-2 测试场地设置

NOKOV 度量动作捕捉在研究中的应用摘录

实验器材：　Nokov-Mars2H 三维动作捕捉系统、25 个标志点、立定跳远软垫、皮尺、剪刀、纵跳摸高器、标志碟、秒表、Elastic resistance band（弹性阻力带）、记录表、签字笔、羽毛球拍两把、VICTOR 羽毛球五桶、一羽毛球网。（2）实验流程正式实验前准备：在正式实验前笔者确定实验测试辅助人员均为羽毛球方向与田径方向研究生（每组测试项目实验前与实验后为同一人），并通过运动生物力学专家指导，熟悉 Nokov 软件系统操作，熟练掌握三维摄像动态捕捉测试流程，确定羽毛球专项步法动作捕捉测试场地并做好标记。

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FAI 和 Coper 患者踝关节扭伤相关动作中的下肢运动生物力学特征

关键词

FAI 患者；Coper 患者；踝关节扭伤相关动作；下肢运动模式

摘要

目的：探讨功能性踝关节不稳定（functional ankle instability,FAI）患者、Coper 患者及健康人群在完成踝关节扭伤相关动作时踝关节运动生物力学特征及功能补偿机制的差异，了解与 FAI 患者重复扭伤相关的运动特征。方法：运用红外光点运动捕捉系统（Nokov Mars2H）和三维测力台（Bertec）获得 FAI 患者（n=10）、Coper 患者（n=10）和健康人群（n=10）完成急停侧切、急停起跳、单腿落地 3 个动作时的下肢运动学和动力学数据。采用 3×3 双因素混合设计方差分析检验不同动作和人群对下肢运动生物力学特征的影响。结果：不同动作和人群对踝关节跖屈角（P=0.039）、踝关节内翻角（P=0.001）、髋关节矢状面活动度（range of motion,ROM）（P=0.044）、膝关节矢状面 ROM(P=0.045)、垂直地面反作用力（ground reaction force,GRF）峰值（P=0.015）和膝关节能量吸收（P=0.050）的交互作用显著。单腿落地时，FAI 患者比 Coper 患者（P=0.027）和健康人群（P=0.012）表现出更大的踝关节跖屈角。急停侧切时，FAI 患者表现出更大的踝关节内翻角速度（Coper 患者：P=0.011；健康人群：P=0.017）、膝关节矢状面 ROM(Coper 患者：P=0.050；健康人群：P=0.002)、膝关节能量吸收（Coper 患者：P=0.049；健康人群：P=0.042）。单腿落地时，FAI 患者的踝关节矢状面 ROM 较 Coper 患者（P=0.001）和健康人群（P=0.004）更大，踝关节能量吸收呈增加趋势（P=0.110）。此外，Coper 患者单腿落地时的垂直 GRF 在 11.6%～13.2%动作周期显著低于 FAI 患者（P=0.037），在 9.8%～12.9%动作周期显著低于健康人群（P=0.019）。结论：Coper 患者在扭伤后表现出与健康人群类似的运动特征。FAI 患者与 Coper 患者和健康人群相比，在单腿落地和急停侧切时表现出踝关节跖屈角、踝关节内翻角速度、踝关节矢状面 ROM、膝关节矢状面 ROM 和膝关节能量吸收增加等运动特征变化，可能与 FAI 患者重复扭伤有关。建议 FAI 患者在训练时除加强踝关节训练外，还需强化膝关节伸肌力量训练，改善下肢着地运动模式，使各关节更有效缓冲 GRF。

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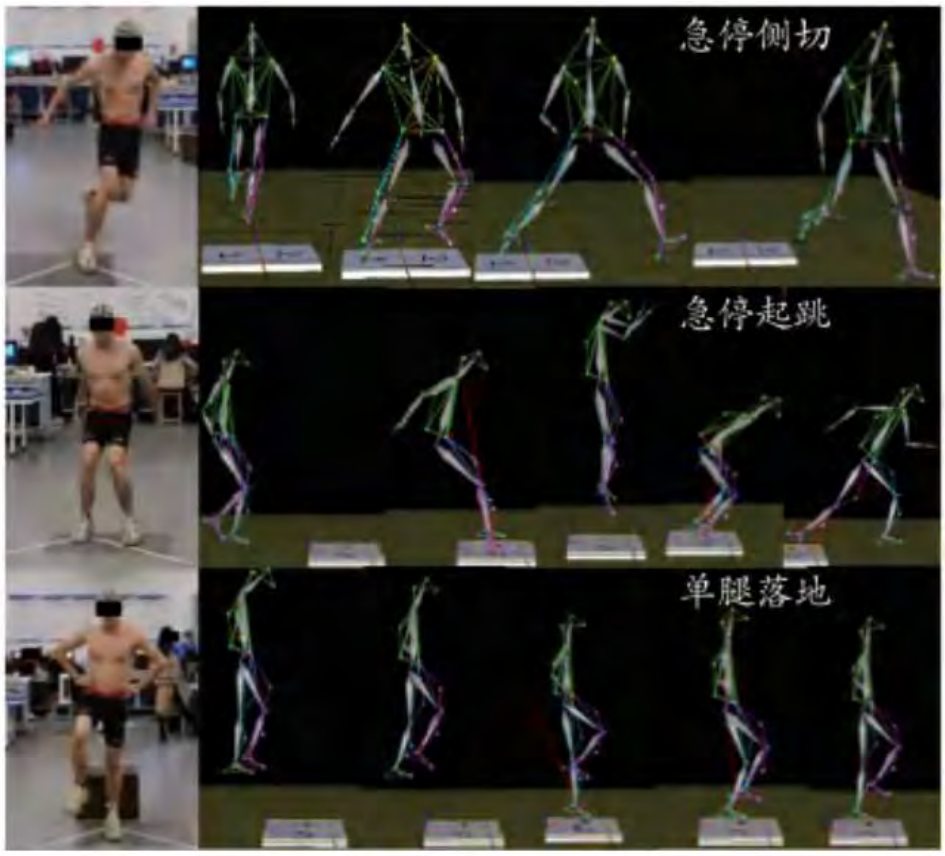

图1　急停侧切、急停起跳和单腿落地动作示意图

NOKOV 度量动作捕捉在研究中的应用摘录

采用 Helen Hayes 粘贴方案将反光 Marker 球（直径为 15 mm）放置于受试者相应骨性标志点。采用 Mars2H 红外光点运动捕捉系统（Nokov，中国）以 200 Hz 的采集频率获得受试者的下肢运动学数据。使用三维测力台（Bertec，美国）通过同步采集卡连接红外镜头，对受试者下肢动力学数据进行同步采集，采样频率为 1000 Hz。每名受试者每个动作均采集 3 次有效数据。

引用格式 张泽毅,刘卉,张美珍等.FAI 和 Coper 患者踝关节扭伤相关动作中的下肢运动生物力学特征[J].中国体育科技，2023,59（08）：47-55.DOI：10.16470/j.csst.2022075.

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FAI 和 Coper 患者在踝关节扭伤高危动作中下肢运动策略的差异

关键词

FAI 者；Coper 患者；踝关节扭伤高危动作；下肢运动策略；

摘要

研究目的：功能性踝关节不稳者（Functional ankle instability,FAI）极易发生踝关节扭伤,特别是在落地、侧切、急停时。已有不少研究关注 FAI 者重复扭伤的生物力学机制,但这些研究多以健康人群作为对照组。由于后者没有任何踝关节扭伤史,两者相比似乎不足以解释 FAI 者重复扭伤的危险机制。最近,有研究提出了 Coper 人群。这种人群只经历过一次踝关节扭伤,并逐步恢复至损伤前的运动状态。将 Coper 人群作为对照组可能对 FAI 者的重复扭伤机制更有说服力。然而,当前关于 FAI 者和 Coper 患者运动策略的比较研究过多聚焦于步行,静态姿势控制等任务上,而真正造成 FAI 者重复扭伤的高危动作（侧切、急停、落地）没有得到充分关注。因此,该研究主要探讨踝关节扭伤高危动作下功能性踝关节不稳定者（Functional Ankle Instability,FAI）和 Coper 患者踝关节运动生物力学以及功能补偿机制的差异。尝试理解 FAI 重复扭伤的生物力学诱因。

研究方法:分别招募 10 名 FAI 者、Coper 患者和健康人群为受试者,运用 12 镜头红外光点运动捕捉系统（Nokov Mars2H,中国）以 200Hz 的采集频率获得受试者落地、侧切、急停时的运动学数据。同时使用 Bertec （美国）三维测力台对受试者的动力学数据进行采集,采样频率为 1000Hz。运用 Cortex-64 2.6.2（Motion Analysis Inc,USA）软件对运动学和动力学数据进行分析和处理,采用欧拉角的方法计算下肢三维角度。通过逆动力学方法计算 GRF 和踝关节三维力矩（MS3D7.0 版,MotionSoft,Inc,美国）。使用关节力矩和关节角速度的乘积计算关节功率。随后,对踝、膝以及髋关节功率负值进行积分,得到各关节做功及能量吸收情况。再用关节力矩的变化/着地至踝关节背屈最大时的矢状面角位移计算关节刚度。最后,采用 3×3 混合设计双因素方差分析（ANOVA）检验不同人群（FAI vs.Coper vs.健康人群）和动作任务（落地 vs.侧切 vs.急停）对下肢运动生物力学的影响。若因素间存在显著性交互作用,则按照不同动作分别通过单因素方差分析比较各人群的下肢运动策略差异。主效应采用 LSD 进行校正,统计分析的显著性标准定为一类误差概率不大于 0.05。其次,本研究使用统计参数映射（statistical parametric mapping,SPM）进一步计算指标达到显著影响的时间范围。

研究结果:双因素方差结果显示,动作和人群对髋关节 ROM（F\[4,81]=2.430,P=0.044）、膝关节 ROM （F\[4,81]=2.421,P=0.045）、垂直 GRF 峰值（F\[4,81]=2.810,P=0.015）和膝关节做功（F\[4,81]=2.238,P=0.05）有显著性交互影响。单因素方差分析结果得出,不同动作下 FAI 者、Coper 患者和健康人群的踝关节内翻角无显著性差异（P > 0.05）。侧切时与健康人群和 Coper

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相比,FAI 者的膝关节 ROM 较大（36.00°vs.29.42°vs.24.26°,P=0.05）。落地时 FAI 者的踝关节 ROM 较 Coper 和健康人群更高（P < 0.05）。除此之外,FAI 侧切时的膝关节做功大于 Coper（P=0.049）和健康人群（P=0.042）。该人群在落地时的踝关节做功也有增大的趋势（P=0.11,P=0.69）。另外,落地时 Coper 患者的垂直 GRF 低于 FAI 者（11.6%-13.2%落地周期）和健康人群（10%-13%落地周期）。

研究结论:与侧切和急停相比,落地表现出更大的下肢 ROM、GRF,更小的到达峰值 GRF 时间。这些指标的变化提示落地时踝关节扭伤风险更大。同时也改变了 FAI、Coper 患者、健康人群的运动策略。具体而言,与 Coper 和健康人群不同,FAI 者在侧切时更依赖膝关节吸收着地冲击力,落地时 FAI 者将地面反作用力重新分配,踝关节成为主要的缓冲关节。而 Coper 人群的运动策略始终与健康人群较为相似,甚至所受地面反作用力低于健康人群。整体看来 Coper 患者的运动策略更为安全,损伤风险较低。该研究的建议是,Coper 患者的运动策略虽与健康人群相似,但并不完全相同。但考虑到 Coper 患者拥有和 FAI 类似的扭伤经历。所以提示对于 FAI 重复扭伤机制的研究应与 Coper 人群进行比较,而不是健康人群。除此之外,FAI 似乎更依赖膝关节和踝关节来缓冲地面反作用力。短期看来,FAI 者可能更易造成膝、踝关节的损伤,所以临床上对于 FAI 者的康复训练不应只关注踝关节本身,还需要注意发展其膝关节的力量。其次,FAI 者的干预训练还应考虑改善下肢整体的运动策略,使地面反作用力均匀的分配在下肢各关节上。

NOKOV 度量动作捕捉在研究中的应用摘录

分别招募 10 名 FAI 者、Coper 患者和健康人群为受试者，运用 12 镜头红外光点运动捕捉系统（Nokov Mars2H，中国）以 200Hz 的采集频率获得受试者落地、侧切、急停时的运动学数据。

引用格式 张泽毅,范婷,杨亦敏等. FAI 和 Coper 患者在踝关节扭伤高危动作中下肢运动策略的差异[A].中国体育科学学会.第十二届全国体育科学大会论文摘要汇编——专题报告(运动生物力学分会)[C].中国体育科学学会：中国体育科学学会，2022：2.DOI：10.26914/c.cnkihy.2022.004226.

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RTMS 联合臀中肌促通对老年脑卒中后偏瘫患者步态、平衡能力和肢体功能的影响

关键词

老年；脑卒中；偏瘫；重复经颅磁刺激；臀中肌促通；步态恢复；肢体功能

摘要

目的 探究重复经颅磁刺激（rTMS）与臀中肌促通联合治疗老年脑卒中后偏瘫的效果，分析对步态、平衡能力和肢体功能的影响，为治疗该病症提供方法。方法 选择 2022 年 10 月—2024 年 3 月南京医科大学附属淮安第一医院收治的 102 例老年脑卒中患者，根据不同的治疗方法分为 rTMS 组和促通组，每组 51 例。2 组均给予常规药物支持治疗与康复训练，rTMS 组给予 rTMS 治疗，促通组在 rTMS 组治疗基础上加用臀中肌反复促通。比较 2 组治疗前后步态、躯干能力[采用中文版躯干损伤量表（TIS）评估]、肢体功能[采用 Fugl-Meyer 评估表（FMA）评估]、平衡能力[采用 Tinetti 平衡与步态量表、伯格平衡量表（BBS）评估及坐位与站立位平衡功能]和血流动力学指标[收缩最大血流速度（PSV）、血流量（BF）]。结果 治疗后，2 组步速、步频、患肢健肢步长比和患肢健肢支撑时间比同组治疗前增加（$P < 0.05$）,步态周期时间和步宽较治疗前减少（$P < 0.05$）,促通组和 rTMS 组差异均有统计学意义（$P < 0.05$）。2 组 TIS 各分量表评分及总分、FMA 中上肢运动和下肢运动和总评分、 Tinetti 评分、 BBS 评分及患侧上肢肱静脉 PSV、 BF 和下肢股总静脉 PSV、 BF 较同组治疗前增加（$P < 0.05$）,重心摆动平均速度、重心移动轨迹和重心单位面积移动轨迹长度较同组治疗前降低（$P < 0.05$）,促通组和 rTMS 组差异有统计学意义（$P < 0.05$）。结论 rTMS 联合臀中肌促通可明显改善老年脑卒中后偏瘫患者步态与平衡能力，增加下肢静脉血流，促进躯干与肢体功能恢复。

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NOKOV 度量动作捕捉在研究中的应用摘录

采用 NOKOV 度量光学三维步态分析系统(北京度量科技有限公司),测量 2 组步速、步频患肢健肢步长比、步态周期时间、步宽和患肢健肢支撑时间比。

引用格式 刘欣荣,易琼.rTMS 联合臀中肌促通对老年脑卒中后偏瘫患者步态、平衡能力和肢体功能的影响[J].老年医学与保健,2024,30(06):1693-1698.

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背包类型对大学生楼梯行走运动学和足底压力的影响

关键词

运动学；负重；背包；足底压力；楼梯行走

摘要

目的分析不同背包类型和载荷对大学生上楼梯行走时运动学和足底压力的影响，为大学生选择合适的背包及携带方式提供参考。方法采用 Nokov 红外光点运动捕捉系统和 Podomed 足底压力测试系统分析 15 名男大学生上楼梯支撑期内躯干和下肢关节活动范围、峰值时刻下肢运动学参数、足底各分区压力峰值、接触时间、全足最大压强、平均压强等参数的差异。结果 5%BW 和 10%BW 背包载荷会减小躯干旋转活动范围（rangeofmotion，ROM），增加踝关节屈伸和内外翻 ROM，10%BW 背包载荷下足底第 1、3 跖骨压力峰值和全足最大压强提升（$P < 0.05$）。单肩包和手提包减小躯干侧倾和旋转 ROM，增大了踝关节屈伸 ROM、髋关节屈曲角、足弓和足跟内侧压力峰值（$P < 0.05$）。双肩包负重增加足趾区的压力峰值（$P < 0.05$）。结论楼梯行走时，5%BW 和 10%BW 背包载荷均会限制躯干旋转，增加踝关节 ROM，10%BW 载荷还会增加足跖区的负荷。单侧负重模式会使躯干向未负重侧倾斜以及向负重侧旋转。携带双肩包时足趾处的压力较高，而单肩包和手提包主要集中增加足弓和足跟内侧压力。建议大学生群体选择对称性背包方案，同时合理分配背包重量避免导致足跖区的损伤。

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NOKOV 度量动作捕捉在研究中的应用摘录

有研究指出，大学生每天携带背包约为 10%BW，结合前人研究与生活实际，本文设置载荷为 0%BW、5%BW 和 10%BW。此外，采用市面上常见的 3 种背包（见图 2）及背带方式进行测试（见表 1）。受试者更换统一的紧身服装，由同一操作人员依据 Helen Hayes 模型贴点方案为受试者粘贴反光标志点。运用 Nokov Mars 2H 红外光点三维运动捕捉系统和足底压力分析系统采集受试者在不同背包负重下以正常速度裸足上楼梯时的生物力学参数，采样频率分别为 200、100 Hz，每个动作均采集 3 次有效数据。

引用格式 闫可，刘艺辉，张泽毅等.背包类型对大学生楼梯行走运动学和足底压力的影响[J].医用生物力学，2023,38（03）：580-586+593.DOI：10.16156/j.1004-7220.2023.03.023.

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不同步态模式下的肌肉协同与大腿截肢者肌肉代偿机制分析

关键词

表面肌电;肌肉协同;非负矩阵分解;肌肉代偿;大腿截肢者;假肢;

摘要

目的 探讨健康人和膝上截肢患肢者健侧下肢与残肢在不同步态时肌肉协同的差异，为假肢的肌电控制提供依据。方法 采集 7 位健康人和 3 位下肢截肢患者在平地行走、上下坡和上下楼梯时 7 块肌肉（4 块大腿肌肉、3 块小腿肌肉）的表面肌电信号，通过级联非负矩阵分解（concatenated non-negative matrix factorization, CNMF）提取肌肉协同权重 W 和时间激活系数 H,利用决定系数 R2 对比 W,基于统计参数映射（statistical parametric mapping, SPM）对比 H,并选取激活峰值和激活积分进行层次聚类。结果 W 对比结果显示，健康组和截肢组健肢存在 1 组相似的协同模式，而残肢侧的协同变异性更高。H 比较表明，所有截肢者在整个步态周期上显示出统计学显著差异。时域特征的聚类表明，截肢被试在上坡时健肢侧肌肉需要更大的激活积分和激活峰值。结论 本研究深入探讨了下肢截肢者在不同步态的神经肌肉代偿策略，有助于对其步态康复提供理论指导，并助力于开发肌电信号控制的假肢。

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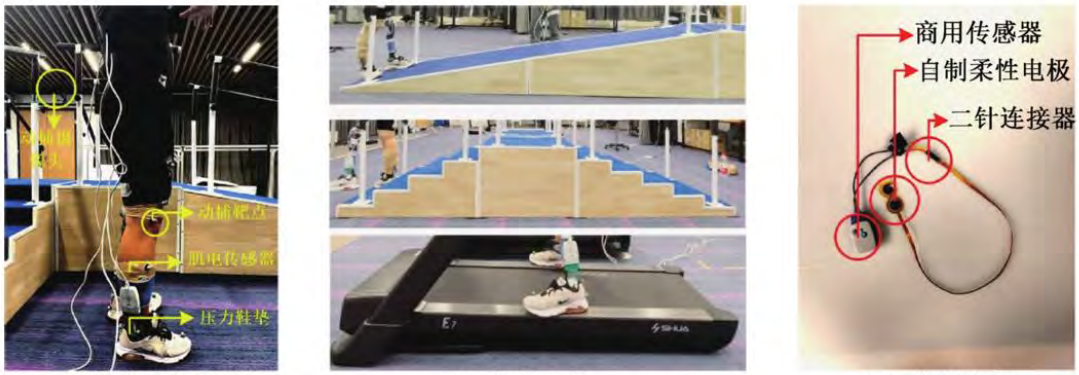

（a）传感器布置　（b）实验场景　（c）自制电极

图 1　健康/截肢被试多元数据采集

NOKOV 度量动作捕捉在研究中的应用摘录

该实验通过 Noraxon 肌电采集系统(采样频率 2 kHz,Noraxon 公司,美国)采集健康被试双腿和截肢被试健肢的臀大肌(gluteus maximus,GF)、股直肌 rectus femoris,RF)、股外侧肌(vastus lateralisVL)、股二头肌(biceps femoris,BF)、胫骨前肌(tibialis anterior,TA)、外侧腓肠肌(gastrocnemiusGM)和比目鱼肌(soleus,s0)共 7 块下肢肌肉的 SEMG 信号。并采集截肢被试残肢侧膝盖上方臀大肌、股直肌、股外侧肌、股二头肌肌肉的肌电信号采用 NOKOV 人体三维运动检测系统(采样频率 100 Hz,北京度量科技有限公司)记录被试髋、膝踝关节角度,并使用 F-SCAN 压力鞋垫(频率 100 Hz, Texscan 公司,美国)识别脚跟着地事件,以作为步态周期(gait cycle,GC)的开始标签。具体的实验场景及肌肉位置如图 1(a)、(b)所示。

引用格式 周润,吕阳,张晓旭,等.不同步态模式下的肌肉协同与大腿截肢者肌肉代偿机制分析[J].医用生物力学,2025,40(02):307-315.DOI:10.16156/j.1004-7220.2025.02.008.

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不同高度跳深时髋、膝关节协调模式与下肢肌肉活动的关系

关键词

跳深；髋关节；膝关节；运动协调；肌肉活动；矢量编码

摘要

背景：异常的关节运动与损伤有关，关节协调常用于分析关节运动，肌肉活动会潜在影响关节间的协调，但目前此方面的研究尚不完善。

目的：分析不同高度跳深过程中髋、膝关节协调模式、肌肉活动水平及二者的相关性。

方法：对 19 名青年男性分别进行 40，60，80 cm 双腿跳深测试，测定臀大肌、半腱肌、股直肌、股外侧肌的肌电活动，计算髋、膝关节角度并采用矢量编码技术计算协调模式。使用单因素重复测量方差比较下肢肌肉活动和髋、膝关节协调模式的变化情况，使用 Pearson 与 Spearman 分析关节协调模式百分比与肌电活动水平的关系。

结果与结论：①在不同高度跳深的触地-起跳阶段，40 cm 与 60 cm、40 cm 与 80 cm、60 cm 与 80 cm 的矢状面同相、远端协调模式百分比差异有显著性意义($P < 0.001$)；②40 cm 与 80 cm、60 cm 与 80 cm 的水平面同相、远端协调模式百分比差异有显著性意义($P < 0.001$)；③半腱肌的肌肉活动在 40 cm 与 60 cm 差异有显著性意义($P < 0.05$)，股直肌的肌肉活动在 40 cm 与 80 cm 差异有显著性意义($P < 0.05$)；④40 cm 时半腱肌的肌肉活动与矢状面的同相协调模式百分比呈正相关($r=0.46$，$P=0.046$)，40 cm 时臀大肌的肌肉活动、80 cm 时股直肌的肌肉活动均与水平面同相协调模式百分比有正相关趋势($r=0.43$，$P=0.064$；$r=0.45$，$P=0.069$)；⑤结果表明，随着跳深高度增加，髋、膝关节同相协调减少、远端膝关节主导的协调增加，40 cm 与 60 cm 跳深时下肢关节具有更好的协调性，预示着在此梯度进行训练的损伤风险较小；肌肉活动水平随着跳深高度增加而增加，其中半腱肌、臀大肌、股直肌的肌肉活动与髋、膝关节协调运动有关。

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NOKOV 度量动作捕捉在研究中的应用摘录

1 对象和方法 Subjects and methods
1.4 实验仪器
1.4.1 运动捕捉系统 8 镜头红外高速运动捕捉系统（ NOKOV， 中国)，采样频率 200 Hz。

引用格式 王佳伟,刘晔.不同高度跳深时髋、膝关节协调模式与下肢肌肉活动的关系[J].中国组织工程研究,2023,27(02):276-281.

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不同缓冲性能乒乓球鞋对人体下肢落地冲击力的影响研究

关键词

生物力学；乒乓球鞋；落地冲击力；踝关节触地角度

摘要

为分析不同缓冲性能的乒乓球鞋在剧烈运动落地时对人体下肢冲击力的影响，选择 20 位乒乓球运动员为研究对象。通过比较研究对象在疲劳干预后穿着不同缓冲性能的乒乓球鞋从 50cm 高处落地时的下肢冲击力、负载率等参数，从生物力学视角下对穿着乒乓球鞋从高处落地时人体下肢的冲击力影响进行分析。结果表明：良好的缓冲能够明显增强人体髋关节、膝关节或是踝关节落地角度变化量，显著增强人体下肢稳定性，但不能显著影响人体落地时踝关节处神经 - 肌肉的控制情况。

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(a) 红外动作捕捉系统

(b) 三维测力台

(c) 心率表

图 1　主要试验设备

NOKOV 度量动作捕捉在研究中的应用摘录

本次研究主要测试运动员在高处落地时下肢受到的冲击力，所使用的设备包括红外动作捕捉系统（NOKOV，北京度量科技有限公司）、三维测力台、心率表等。红外动作捕捉系统用于对研究对运动员纵跳落地过程中的髋、膝、踝关节触地角度、最小角度等参数进行获取。

引用格式　刘娜.不同缓冲性能乒乓球鞋对人体下肢落地冲击力的影响研究[J].中国皮革,2023,52(10):99-103.DOI:10.13536/j.cnki.issn1001-6813.2023-010-023.

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不同跑速对膝内翻跑者下肢运动学特征的影响

关键词

膝内翻；跑速；损伤；运动学分析

摘要

跑步是人们最常参与的体育锻炼项目，但是跑步会对跑步爱好者下肢造成不同程度的损伤，其中大多数损伤发生在膝关节处。在不同跑速下膝关节屈曲角以及受到的地面反作用力有所不同，并且不同腿型在支撑期膝内翻人群的内翻外翻角、内旋外旋角大于直腿人群。本文采用实验法试图分析不同腿型与不同跑速对业余跑者下肢的运动学影响，尝试了解不同腿型、不同跑速与下肢的运动学差异。实验数据表明膝内翻组与直腿组在 3m/s 和 5m/s 跑速下左右膝关节落地时刻屈伸角存在显著差异，在整个支撑期间相同跑速下膝内翻组内翻外翻角与直腿组相似，膝内翻组内旋外旋角大于直腿组。最后通过研究结果得出研究结论与建议，在 3m/s 的跑速下跑步会减少运动损伤，无论膝内翻人群还是直腿人群建议选择 3m/s 的跑速进行锻炼。并且在相同跑速下跑步时膝内翻人群会造成额外的损伤，增加膝关节损伤的概率。

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NOKOV 度量动作捕捉在研究中的应用摘录

本实验采用 8 镜头红外光点运动捕捉系统（Nokov，中国）以 200Hz 的采集频率获取 29 个粘贴在受试者身上的红外反光标志点的运动学数据。

引用格式 张宇强,关景媛.不同跑速对膝内翻跑者下肢运动学特征的影响[J].文体用品与科技,2022(15):61-63.

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不同坡度后退走对下肢运动学和足底压力的影响

关键词

后退走；向前走；斜坡坡度；运动学；足底压力

摘要

【目的】探究不同坡度后退走对下肢关节运动学和足底压力特征的影响，为更有效、更科学地将后退走应用于训练和损伤康复等方面提供参考。【方法】运用三维红外光点运动捕捉系统（Nokov，中国）和足底压力步态分析系统（Podomed，中国）采集普通大学生运动学和足底压力数据。通过 2×3 重复设计的双因素方差分析确定坡度和行走方向对下肢关节运动生物力学的影响。【结果】后退走较向前走，着地时刻髋关节在 0°、6°和 9°斜坡表现出较小的屈曲角；在 0°斜坡表现出较小髋关节和膝关节屈曲角活动范围，6°和 9°斜坡表现出较小髋关节屈曲角活动范围。后退走较向前走在 0°和 6°斜坡中表现出较大的第一趾骨峰值压力，在 6°和 9°斜坡中表现出较小的足底最大压强。【结论】后退走在斜坡上可以更好的避免膝关节损伤发生，可用于下肢力量训练；斜坡上后退走有助于更好地保持平衡，可作为由于足底受力过大导致足踝损伤的预防及康复手段。

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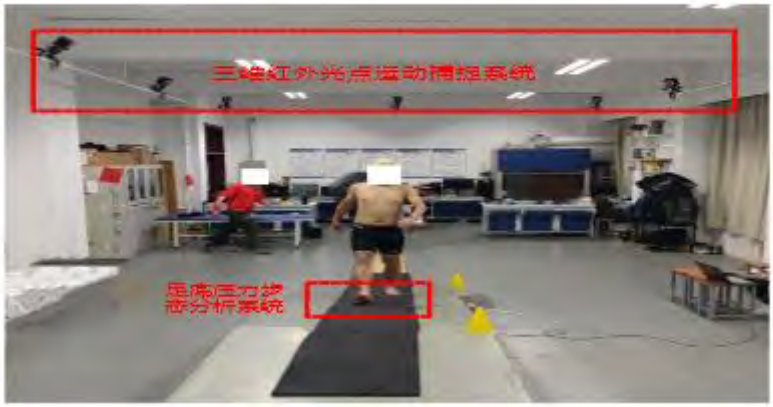

NOKOV 度量动作捕捉在研究中的应用摘录

根据 H.HAYES 模型由同一操作人员为受试者粘贴 29 个反光标志点[8]。采用 12 镜头三维红外光点运动捕捉系统（Nokov，中国）以 200Hz 的采集频率进行运动学数据采集，同时运用足底压力系统步态分析系统（Podomed，中国）以 100Hz 的采集频率进行足底压力数据采集。

引用格式 贾敏,侯捷,闫可等.不同坡度后退走对下肢运动学和足底压力的影响[J].体育科技,2023,44(03):31-35.DOI:10.14038/j.cnki.tykj.2023.03.013.

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不同坡度后退走下肢运动生物力学特征分析

关键词

后退走；向前走；斜坡坡度；运动学；足底压力

摘要

研究目的：后退走作为一种运动形式且有别于向前走,已成为运动训练和损伤康复的主要手段之一，然而在不同坡度上后退走时下肢运动学及足底压力特征尚不清晰。本文通过分析健康大学生在不同坡度上后退上坡走时的运动生物力学参数，以期揭示斜坡坡度对后退上坡走时下肢运动生物力学的影响，为更有效、更科学地将后退走应用于训练和损伤康复等方面提供参考。

研究方法：本研究募集了 23 名健康男性大学生，采用 12 镜头三维红外光点运动捕捉系统(Nokov，中国)以 200Hz 的采集频率进行运动学数据采集，测试过程中要求受试者以自选舒适速度分别在不同坡度（0°、6°、9°）下后退和向前上坡走各 3 次，同时运用足底压力步态分析系统（Podomed，中国）进行足底压力数据采集。运用 Cortex 软件和 P-Plate-scientific 分析软件分别对运动学和足底压力数据进行处理。通过 2×3 重复设计的双因素方差分析（SPSS 22.0）确定不同坡度和行走方向对下肢关节运动学和足底压力的影响，若存在交互作用，则运用配对样本 t 检验比较行走方向间的区别，通过单因素方差分析确定不同坡度间的差异，所有统计分析显著性标准定为一类误差概率小于 0.05。

研究结果：(1)着地时刻，髋关节屈曲角和内收外展角在坡度与行走方向间存在显著性交互作用（$p < 0.001$）。在 0° 斜坡后退走较向前走髋关节表现出较小的屈曲角（$p < 0.001$）和较大的内收外展角（$p = 0.004$），在 6° 斜坡和 9° 斜坡时髋关节表现出较小的屈曲角（$p < 0.001$）和内收外展角（$p < 0.001$）。髋关节和膝关节屈曲角活动范围在坡度与行走方向间存在显著性交互作用（$p < 0.001$）。后退走较向前走在 0° 斜坡表现出较小髋关节（$p=0.014$）和膝关节（$p < 0.001$）屈曲角活动范围，在 6° 斜坡和 9° 斜坡表现出较小髋关节屈曲角活动范围（$p < 0.001$），后退走在 0° 斜坡较 6° 斜坡表现出较大的髋关节屈曲角活动范围（$p=0.003$）和较小的膝关节屈曲角活动范围（$p=0.015$），在 0° 斜坡较 9° 斜坡表现出较大的髋关节屈曲角活动范围（$p < 0.001$）。向前走在 0° 斜坡较 6° 斜坡和 9° 斜坡现出较小的髋关节屈曲角活动范围（$p=0.003$，$p < 0.001$）和较大膝关节屈曲角活动范围（$p=0.008$，$p=0.005$）。 (2)第一趾骨峰值压力在坡度和行走方向间存在显著性交互作用（$p=0.031$）。后退走较向前走在 0° 斜坡（$p=0.001$）和 6° 斜坡（$p < 0.001$）中均表现出较大的第一趾骨峰值压力。向前走在 0° 斜坡较 6° 斜坡表现出较小的第一趾骨峰值压力（$p < 0.001$），6° 斜坡较 9° 斜坡表现出较小的第一趾骨峰值压力（$p < 0.001$）。不论斜坡坡度，后退走较向前走表现出较小的第一、二、四、五跖骨及足弓、足跟内外侧峰值压力（$p < 0.001$）和足轴角（$p < 0.001$），较大的第三跖骨峰值压力（$p < 0.001$）。不论行走方向，0°斜坡较 9° 斜坡表现出更大的足弓（$p=0.041$）、足跟内侧（$p=0.024$）、足跟外侧

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峰值压力（$p < 0.001$）；0° 斜坡较 6° 斜坡表现出较小的足跟外侧峰值压力（$p=0.021$）。足底最大压强在坡度和行走方向间存在显著性交互作用（$p=0.048$）。后退走较向前走在（$p=0.025$）和 9° 斜坡中（$p=0.010$）均表现出较小的最大压强。

研究结论：（1）后退走在着地时刻，人体为获得更好的稳定性，下肢关节通过增加髋关节、膝关节屈曲角度适应新的步态模式。随着坡度的增加，行走过程中髋关节屈曲角活动范围减少，膝关节和踝关节屈曲角活动范围增加，其对远端关节运动策略的改变与正常行走相比表现出不同的代偿机制。（2）与向前走相比后退行走时足底第一跖骨处压力增加，增加了人体向后的推进力，有效地预防足跟的运动性损伤，但可能会增加踝关节损伤风险。随着坡度的增加，后退走表现出较小的足底最大压强和足轴角，使步态更趋于平稳并减轻足底的负荷，身体运动能力和平衡能力的效果会更好。

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图 2.2-2a 静态标定—正面　图 2.2-2b 静态标定—背面

图 2.2-2 静态标定

Figure 2.2.3-2 The subjects taken static

NOKOV 度量动作捕捉在研究中的应用摘录

2.2.3 运动学数据采集
根据 H.HAYES 模型在受试者身上由同一人粘贴 29 个反光标志点\[65]（表 2.2-1），同时由同一人对受试者进行测试动作的讲解、示范，并说明注意事项。采用 12 镜头三维红外光点运动捕捉系统(Nokov，中国）以 200 Hz 的采集频率，采集受试者在长 3 米、 坡度为 0°、6°、9°的斜坡上进行后退走和向前走上坡时下肢运动学数据，每个受试者每个动作均采集 3 次有效数据。测试开始前需要对受试者进行静态标定，标定空间为测试区域上方 3.0 m×2.5m×2.5 m 的范围（图 2.2-2）。动作要求：受试者进入标定区域， 双脚前后开立，略比肩宽，两臂侧平举，面向镜头，保持 5 秒。静态标定的标准：与拍摄系统相连接的电脑上的十二个显示框中均无杂点出现时即为静态标定完成。

引用格式 贾敏.不同坡度后退走下肢运动生物力学特征分析[D].太原理工大学，2022.DOI：10.27352/d.cnki.gylgu.2022.000657.

链接
https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CMFD&dbname=CMFD202202&filename=1022739020.nh&uniplatform=NZKPT&v=AN-7u0qQVauPfzvxQi0H5YZSAmqn6DaFD3Gowowjh9E3Su20VUaA0bgDJNHyehin

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不同躯干约束下蹲姿对人体下肢运动学和动力学的影响

关键词

亚洲蹲；西方蹲；躯干控制；运动学；动力学

摘要

目的 探究躯干控制对青年群体亚洲蹲和西方蹲时下肢运动生物力学特征的影响，为深蹲训练的应用和推广提供实证性依据。方法 24 名健康男性青年大学生在带杆、无杆控制条件下进行亚洲蹲和西方蹲，运用红外光点运动捕捉系统和三维测力台采集其下肢运动学和动力学特征。通过 Cortex-642.6.2 软件，根据欧拉角的方法计算获得下肢三维角度，运用逆动力学方法得到三维力矩。通过 2×2 重复设计的双因素方差分析检验躯干控制和深蹲姿势对下肢运动特征的影响。结果 躯干控制和深蹲姿势对运动学和动力学参数均无显著性交互作用（P>0.05）。西方蹲具有较大的膝关节屈曲角、髌股关节接触力峰值、髋膝伸展力矩峰值之比（P<0.05），较小的踝关节背屈角、髋关节屈曲角（P<0.001）。带杆深蹲具有较大的踝关节背屈角、髌股关节接触力峰值和髋关节屈曲角（P<0.05），较小的膝关节屈曲角、髋膝伸展力矩峰值之比（P<0.001）。结论 西方蹲有助于训练伸髋肌群肌力，亚洲蹲则有助于训练伸膝肌群肌力。西方蹲髌股关节接触力峰值显著大于亚洲蹲，故推荐髌股关节痛患者采用亚洲蹲。带杆深蹲可补偿人体平衡，建议由于踝关节背屈活动范围受限或胫骨前肌无力人群可以考虑进行带杆深蹲等躯干控制训练，有助于帮助提高深蹲时下肢稳定性。

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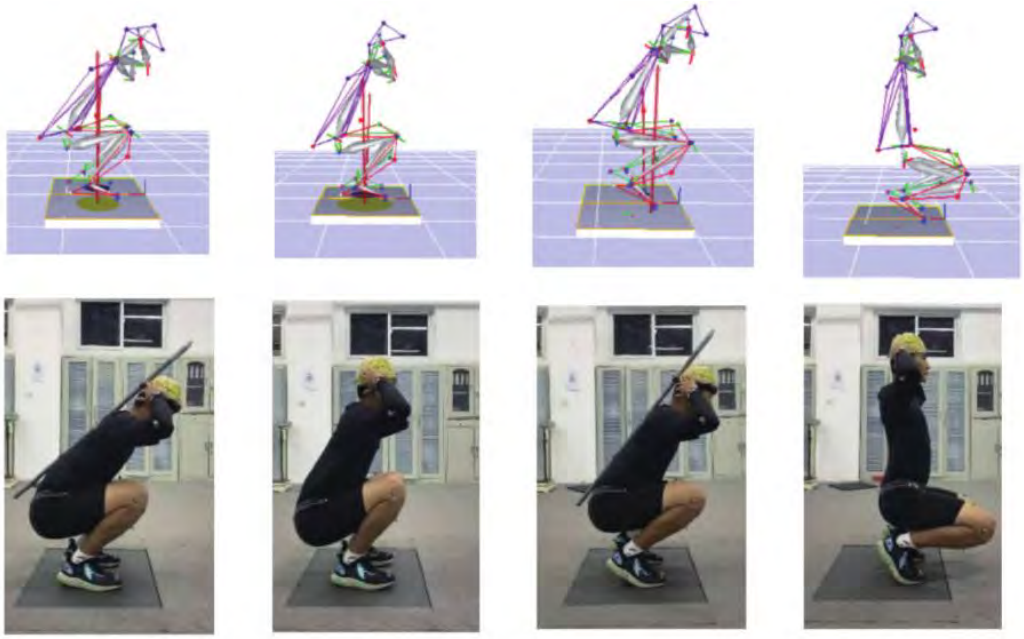

（a）带杆亚洲蹲（b）无杆亚洲蹲（c）带杆西方蹲（d）无杆西方蹲

图 1　深蹲姿势示意图

NOKOV 度量动作捕捉在研究中的应用摘录

测试过程中，运用 １２ 镜头红外光点三维运动捕捉系统（Ｎｏｋｏｖ Ｍａｒｓ２Ｈ，北京度量科技有限公司）及三维测力台（Ｂｅｔｅｃ 公司，美国）同步采集运动学和动力学数据，采样频率分别为 ２００、１ ０００ Ｈｚ。每名受试者每个动作均采集 ３ 次有效数据。

引用格式 郝乐天，陈纪均，杨亦敏等.不同躯干约束下蹲姿对人体下肢运动学和动力学的影响[J]. 医用生物力学，2024,39（01）：118-124.DOI：10.16156/j.1004-7220.2024.01.017.

链接
https://kns.cnki.net/kcms2/article/abstract?urlId=31.1624.R.20230718.1428.002&uniplatform=NZKPT

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不同认知任务跑步时髌股关节痛患者下肢运动学和动力学特征

关键词

运动生物力学；髌股关节痛患者；髌股关节应力；认知任务；跑步

摘要

明确髌股关节痛患者在不同认知任务跑步时下肢运动学和动力学特征的影响，旨在寻找降低髌股关节痛患者跑步时髌股关节应力的运动模式。招募 46 名男性髌股关节痛患者为实验对象，运用红外光点运动捕捉系统(NOKOV Mars2H)和三维测力台(Bertec)获得其在无任务、音乐任务和心算任务跑步时的运动学和动力学特征。采用重复测量方差分析确定不同认知任务对下肢运动生物力学参数的影响，通过 Pearson 双变量相关探究下肢运动生物力学特征与髌股关节应力的关系。结果显示：(1)与无任务相比，音乐任务与心算任务均使髌股关节痛患者步长增大($P<0.001$)；音乐任务还使其膝关节屈角增加($P=0.005$)、踝关节跖屈力矩减小($P=0.022$)；心算任务减小髋关节内收力矩($P<0.05$)和步频($P<0.001$)。(2)无论何种认知任务，步长、膝关节屈曲角与髌股关节应力峰值正相关($P<0.05$)，踝关节跖屈力矩($P<0.05$)与髌股关节应力峰值呈负相关。心算任务下，髋关节内收力矩($R2=0.162, P=0.006$)和步频($R2=0.123, P<0.017$)等与髌股关节应力峰值呈负相关。研究认为：髌股关节痛患者在音乐任务跑步时膝关节屈曲、踝关节背屈和步长增加可能会增大髌股关节应力，在心算任务跑步时较小的髋关节内收、长步长和慢步频等运动特征，可能使髌股关节应力增加。建议髌股关节痛患者在听音乐跑步时，应采用膝关节更为直立的动作模式降低髌股关节应力，还应注意减小步长。此外，还可通过增强髋关节内收及踝关节跖屈肌群的力量来减小髌股关节应力，预防跑步时思维游离引起的疼痛复发。

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图 3　目标物位姿估计实验平台

Fig.3　Object pose estimation experimental platform

NOKOV 度量动作捕捉在研究中的应用摘录

有效的心算任务是要求受试者在测试过程中连续跑步并保 证计算结果正确，若计算错误则重新测试。通过随机 生成器随机模拟以上 3 种任务，运用 12 镜头红外光点 运动捕捉系统(Nokov Mars 2H，中国)以 200 Hz 的采样 频率获得三维运动学数据，通过三维测力台(Bertec 4060-08，美国)以 1 000 Hz 采集频率同步采集下肢动 力学特征，每种任务均采集 3 次有效数据。

引用格式 范婷，张美珍，张力文等.不同认知任务跑步时髌股关节痛患者下肢运动学和动力学特征[J].体育学刊，2023,30（03）：136-144.DOI：10.16237/j.cnki.cn44-1404/g8.2023.03.009.

链接

https://kns.cnki.net/kcms2/detail/44.1404.G8.20230530.1447.022.html

不同弯曲刚度鞋垫对跑步过程中下肢生物力学影响研究

关键词

弯曲刚度；个性化鞋垫；生物力学特征；慢跑运动

摘要

为分析鞋垫刚度对跑步过程中人体下肢生物力学特征影响，定制了 4 种不同弯曲刚度鞋垫（低、中、较高、高），筛选 20 位具有一定跑步经验的 20 岁男性大学生为研究对象，借助三维动作捕捉系统等装置对其穿着不同刚度鞋垫时，人体下肢踝关节运动学、动力学等情况进行分析。结果表明，鞋垫的弯曲刚度并不是越大/越小越好，选择适中或较高弯曲刚度的鞋垫通常能够保证最佳运动学、动力学指标，还能一定程度上保证鞋垫的舒适性。

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（a）动作捕捉设备

NOKOV 度量动作捕捉在研究中的应用摘录

试验采集的受试者跑步过程中的运动学参数和动力学参数。使用北京度量科技有限公司出品的 NOKOV Mars 1.2H 红外线动作捕捉设备，分辨率 1200 万像素，频率 300Hz，可直接获取足外旋角度、峰值踝关节内/外翻角速度等数据。

引用格式 王永鹏.不同弯曲刚度鞋垫对跑步过程中下肢生物力学影响研究[J].中国皮革,2023,52(12):82-86+91.DOI:10.13536/j.cnki.issn1001-6813.2023-012-018.

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https://kns.cnki.net/kcms2/article/abstract?v=lxlxReJOxldrBRQJ6iWMmVzMexk3gQypTPojnsCyK9x7xr5NKj2s1ji8wb9e1emAK-u9QLrGXBPB79IKxs-dUxWy0cm6ZLlwt5Yks9Cak4vyweaNONzlPQ==&uniplatform=NZKPT&language=gb

不同运动性疲劳方案对足球专项大学生躯干和下肢运动学特征的影响

关键词

运动性疲劳；跳箱单脚落地起跳；急停侧切；运动学

摘要

目的：对比分析足球专项体能测试（SAFT90）和 Yo-Yo 间歇耐力水平 2 测试（Yo-Yo IE2）对运动员着地时刻神经肌肉控制的影响。方法：选取 7 名大学生足球专项运动员为受试，运用红外光点运动捕捉系统（Nokov Mars2H）获得运动学数据。受试佩戴心率实时监测遥测仪（Polar Team 2），用于保障实验的安全性和疲劳评价的有效性与客观性。运用 2×2 重复测量设计的双因素方差分析验证 2 种动作下疲劳诱导和疲劳方案对运动特征的影响。结果：受试完成的 2 种疲劳方案均达到疲劳评定标准，心率和自感疲劳等级均无显著性差异。单脚落地起跳动作着地时刻，髋关节内外旋角 F（1，6）=7.811，P=0.031，r=0.752］和膝关节内外翻角［F（1，6）=6.976，P=0.038，r=0.733］对疲劳方案及疲劳诱导具有显著性交互作用。与 SAFT90 疲劳诱导前相比，诱导后髋关节矢状面活动度增加（13.6° vs 18.5°，P=0.022，r=0.783）、髋关节内旋（-5.9° vs 2.6°，P=0.019，r=0.793）、膝关节外翻（2.1° vs -1.5°，P=0.001，r=0.928）、外旋（-12.8° vs -20.3°，P < 0.001，r=0.968）增加。侧切着地时刻膝关节屈曲角［F（1，6）=14.164，P=0.009，r=0.838］和膝关节内外翻角［F（1，6）=17.679，P=0.006，r=0.864］在疲劳方案及疲劳诱导间存在显著性交互作用。SAFT90 疲劳诱导后侧切时更趋于足跟着地（-3.8cm vs -6.9cm，P=0.031，r=0.753）。结论：足球运动员疲劳诱导后完成动作的着地策略与疲劳前不同，特别是 SAFT90 运动性疲劳诱导后，其单脚落地跳着地时刻髋关节内旋、膝关节外翻、外旋显著增加；急停侧切着地时刻，膝关节更加直立、外翻，同时趋于足跟着地，可能增加疲劳后前交叉韧带损伤风险。完成 Yo-Yo IE2 运动性疲劳诱导后，足球运动员急停侧切时膝关节外翻角度增加，且 SAFT90 较 Yo-Yo IE2 运动性疲劳诱导方案对足球运动员的影响更大。提示，采用 SAFT90 作为足球运动性疲劳诱导方案，对于理解下肢疲劳后的神经肌肉控制可能更有参考价值。

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图1　受试者测试动作示意图

Figure 1.　Testing Maneuvers of Participants

注：a.单脚落地起跳；b.侧切。

NOKOV 度量动作捕捉在研究中的应用摘录

1.2 数据采集
运用红外光点运动捕捉系统（ Nokov Mars2H）以 200 Hz 的采集频率获得受试者运动学数据，每名受试者每个动作均采集 3 次有效数据。测试过程中， 受试者佩戴心率实时监测遥测仪（Polar Team2）对心率进行监控 ，用于保障实验的安全性和疲劳评价的有效性与客观性。

引用格式 张美珍，郭浩，刘卉等.不同运动性疲劳方案对足球专项大学生躯干和下肢运动学特征的影响[J].中国体育科技，2022,58（08）：32-40.DOI：10.16470/j.csst.2021012.

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https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFDLAST2022&filename=ZGTY202208005&uniplatform=NZKPT&v=wamzFxv1Y_st77WLjGCCEMePev694b5xkWA_6aZ32_SVIOEBzfhPv_dHq6DDGbJf

侧切状态下篮球运动员下肢生物力学特征及影响因素研究

关键词

篮球运动； 侧切模式； 人体下肢； 生物力学特征

摘要

篮球运动中存在大量的侧切动作，侧切动作的不同模式会对运动员的下肢各关节形成不同的影响。本文以 10 位达到国家二级运动员水平的男性篮球运动员为研究对象，分析了后足落地、中足落地、前足落地 3 种不同侧切状态下篮球运动员下肢（膝关节）的生物力学特征。结果表明，采用后足落地侧切形式时，人体下肢膝关节峰值屈曲角度、活动度、反作用力峰值均更高，此时人体下肢更容易出现运动损伤；采用前足落地侧切形式时，更不容易出现运动损伤，且侧切变向、蹬伸效果更好。

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其中，人体动作捕捉系统采用 NOKOV 度量光学三维动作捕捉系统，设定采样频率为 2 0 0 H z。下肢反光标志点粘贴情况如表 2 所示。左右两腿内外侧膝关节中心位置各布置 1 个反光标志点，共计 4 个；左右两足足跟追踪点各布置 1 个，共计 2 个；左右两足第一趾骨头各布置 1 个，共计 2 个；左右两足第五趾骨头各布置 1 个，共计 2 个。

引用格式 刘训.侧切状态下篮球运动员下肢生物力学特征及影响因素研究[J].中国皮革,2024,53(11):51-54+61.DOI:10.13536/j.cnki.issn1001-6813.2024-011-010.

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断接引流线夹作业姿势和肌肉疲劳的实验室模拟分析

关键词

表面肌电信号；带电作业；工效学；动作捕捉；肌肉疲劳；作业姿势

摘要

[背景] 带电作业人员从事上肢作业时，长时间的举臂操作以及其他不良因素的存在易增加肌肉负荷，引起疲劳积累，增加发生工作相关肌肉骨骼疾患的风险。[目的] 分析从事断、接引流线夹的作业姿势和肌肉负荷及疲劳情况，探讨作业过程中存在的不良工效学因素。[方法] 招 募 10 名大学生志愿者进行断、接引流线夹模拟试验，分别在电线距离人体高度 4.5、3.5 和 2.5 m 处各进行 5 次连续断、接引流线夹操作，动捕数据采用 Visual 3D 软件进行处理分析，获得上肢目标关节三维角度。记录模拟试验过程中志愿者三角肌、肱二头肌、肱三头肌和肱桡肌处的表面肌电信号。采用均方根值（RMS）、中位频率（MF）和联合频谱振幅分析（JASA）对作业过程中局部肌肉疲劳情况进行分析。每完成一次操作后使用 Borg 主观疲劳评定量表询问志愿者主观疲劳感受，让志愿者在量表的疲劳评分区间中选择最符合自身疲劳感觉的分值，每完成一个高度的 5 次操作后需休息 20 min 后再进行下个高度的试验。[结果] 动捕数据结果显示，在整个作业过程中，右手为抬举更高的一侧，右侧肩关节全程保持屈曲且在外展与内收、外旋与内旋间周期性波动，右侧肘关节则全程保持屈曲和旋后。完成作业次数对受试者 Borg 量表评分有显著影响（$P < 0.001$，偏=0.464）；导线高度对 Borg 量表评分无显著影响（$P > 0.05$，偏=0.002）；两者的交互效应不显著（$P > 0.05$，偏=0.020）。肌电信号结果显示，在高度 为 4.5 m 的情况下，志愿者完成 5 次作业操作后两侧三角肌和右侧肱桡肌的最大自主收缩肌电百分比（MVE%）最高，两侧三角肌和左侧肱桡肌的 MF 值最低；JASA 分析结果显示，在 4.5 m 高度完成 5 次作业后，两侧肱桡肌和三角肌出现疲劳；在 3.5 m 高度完成 5 次作业后，右侧三角肌和右侧肱桡肌出现疲劳；在 2.5 m 高度完成 5 次作业后，左侧肱二头肌、两侧肱桡肌和三角肌出现疲劳。[结论] 从事断、接引流线夹作业的人员主观疲劳感受随着重复作业次数的增加而愈发明显。基于表面肌电信号和动作捕捉分析可以发现，作业人员与目标工作区域的距离过远或过近，均能增加来自不良姿势、不恰当工器具使用的负担，易导致肌肉疲劳的发生；三角肌和肱桡肌是该类型作业肌肉疲劳的关键肌群；在操作过程中肘关节和肩关节活动角度的变化，可影响三角肌和肱桡肌的用力和负荷情况。

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图 2 受试者反光标记点放置示例

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本研究采用 NOKOV 光学三维动作捕捉系统实现运动学数据的收集与处理，该系统包括 12 台高精度红外摄像头和 1 套三维动作捕捉建模软件。软件中的 25 点人体上肢模型能够匹配本研究的需求，实现对肩关节和肘关节活动情况的记录，通过摄像头捕捉贴放于受试者身体上的反光标记点，可在软件中浏览到各关节在作业过程中的运动轨迹。反光标记点放置示例见图 2。

引用格式 潘锐健,陆新,刘聪汉,等.断接引流线夹作业姿势和肌肉疲劳的实验室模拟分析[J].环境与职业医学,2025,42(03):260-269.

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多方向足球比赛模拟协议对足球运动员在高危动作下 ACL 损伤的运动学分析

关键词

ACL;模拟协议;性疲劳;

摘要

目的为探讨足球特异性疲劳对足球运动员做高危动作时 ACL 损伤的运动学影响，通过 SAFT 协议诱发足球特异性疲劳，分析疲劳前、后足球运动员下肢运动学特征差异，进一步探讨运动性疲劳对 ACL 损伤的危险机制及因素。方法选取 20 名足球专项男运动员且运动年限为 2 年以上为受试者并进行 SAFT 模拟协议来诱发特异性疲劳。运用 8 镜头 Nokov 红外光点捕捉系统分别采集受试者在完成垂直纵跳、单脚落地跳跃及急速侧切动作疲劳前、后的运动学特征数据。通过 Cortex 软件对运动学数据处理得到膝关节三维角度。利用重复测量双因素方差分析等方法对结果进行统计分析。结果 ACL 损伤膝关节运动学指标在不同高危动作及疲劳前、后均存在极显著性差异（$P < 0.01$）。疲劳前、后侧切动作较单脚落地跳跃与垂直纵跳动作在膝关节屈角及内旋角表现均具有显著性差异（$P < 0.05$）。疲劳后较疲劳前落地时刻膝关节屈角显著减小（$P < 0.01$），膝关节外展角显著增大（$P < 0.05$）。结论较小的膝关节屈角、较大的膝关节外展角和内旋角等使 ACL 损伤的风险更大，研究发现侧切和单脚落地跳较垂直纵跳更易引起 ACL 损伤，总之足球特异性疲劳是足球运动员 ACL 损伤的危险因素。（山西省高等学校哲学社会科学基金一般项目：2014233；太原理工大学校基金青年项目：2015RS020；太原理工大学大学生创新创业训练项目）。

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NOKOV 度量动作捕捉在研究中的应用摘录

目的为探讨足球特异性疲劳对足球运动员做高危动作时 ACL 损伤的运动学影响，通过 SAFT9°协议诱发足球特异性疲劳，分析疲劳前、后足球运动员下肢运动学特征差异，进一步探讨运动性疲劳对 ACL 损伤的危险机制及因素。方法选取 20 名足球专项男运动员且运动年限为 2 年以上为受试者并进行 SAFT9°模拟协议来诱发特异性疲劳。运用 8 镜头 Nokov 红外光点捕捉系统分别采集受试者在完成垂直纵跳、单脚落地跳跃及急速侧切动作疲劳前、后的运动学特征数据。通过 Cortex 软件对运动学数据处理得到膝关节三维角度。利用重复测量双因素方差分析等方法对结果进行统计分析。结果 ACL 损伤膝关节运动学指标在不同高危动作及疲劳前、后均存在极显著性差异（P < 0.01）。疲劳前、后侧切动作较单脚落地跳跃与垂直纵跳动作在膝关节屈角及内旋角表现均具有显著性差异（P < 0.05）。疲劳后较疲劳前落地时刻膝关节屈角显著减小（P < 0.01），膝关节外展角显著增大（P < 0.05）。结论较小的膝关节屈角、较大的膝关节外展角和内旋角等使 A C L 损伤的风险更大，研究发现侧切和单脚落地跳较垂直纵跳更易引起 ACL 损伤，总之足球特异性疲劳是足球运动员 ACL 损伤的危险因素。（山西省高等学校哲学社会科学基金一般项目： 2014233；太原理工大学校基金青年项目：2015RS R S2020；太原理工大学大学生创新创业训练项目）。

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多环境蛇运动接触分析及其鳞片摩擦性能测试研究

关键词

赤链蛇；多环境；运动学；接触力学；摩擦性能

摘要

蛇作为一种无腿的特殊爬行动物，具有自身灵活多态的身体结构与全身覆瓦状排列的耐磨鳞片，通过二者的耦合效应，表现出对复杂环境地貌的优越适应能力。根据蛇生活习性，选择半水栖的赤链蛇作为研究对象，探究多种环境下蛇运动接触行为及其鳞片摩擦性能，揭示蛇在复杂环境下的运动策略，为蛇形机器人的运动系统提供有效的仿生设计依据。首先运用三维动作捕捉系统，探究了赤链蛇在多种环境下的运动学规律。试验结果表明，赤链蛇利用身体肌肉，依靠侧部和腹部鳞片与接触面相互交替配合，形成手风琴式张合形态，实现多环境下蛇伸缩式运动。通过改变粗糙度、干湿性等接触环境，观测蛇运动参数及接触点个数，发现蛇通过肌肉调控身体进行位移，并在确保运动稳定性条件下，调整运动速度。

其次综述了当前国内外动物运动接触力学测试装置，并根据蛇生活习性，设计搭建了赤链蛇运动接触力学测试装置，探究蛇在不同运动空间内运动时身体移动单元受力变化。试验结果分析发现，赤链蛇在通道内运动时，与其身体单元接触的传感器显示的接触力接近，但随着通道宽度的增加，腹部接触力增大，表明蛇具有重新分配自身体重的功能，也证明随通道宽度增大，蛇前进的主要动力来源逐渐转变为腹部接触力提供。

最后运用多功能摩擦磨损试验机，探究了不同粗糙度下，腹部鳞片的摩擦润滑性能。试验数据表明，湿环境下腹鳞的摩擦因子要大于干环境下腹鳞的摩擦因子，且干环境下，随着滑行速度的增加，腹鳞摩擦因子呈现降低趋势，而湿环境下，随着滑行速度的增加，腹鳞摩擦因子却呈现增大的趋势，表明蛇依靠腹部接触力运动时，随着环境的改变，蛇通过调控腹部鳞片相关性能实现周期、速度和位移的改变。

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图 2.3 三维动作捕捉系统及测试通道

NOKOV 度量动作捕捉在研究中的应用摘录

针对本试验测试需求，选择 NOKOV 三维动作捕捉系统对赤链蛇运动行为进行观测。NOKOV 系统由 Mars4H 高速动作捕捉镜头、镜头固定套件、镜头专用连接线、POE 交换机、PC 主机、光学标定系统套件和捕捉专用反光球（标记点）等组成，可用于测量动物运动学、人体运动学和机器人运动学等相关数据，包括位置、距离、速度、加速度、角度等。该系统测试原理是通过红外摄像镜头释放红外线，经过待测对象表面标记点反射后再次对红外线进行自动捕捉、侦测和识别，从而对待测对象三维空间运动进行监测，同时可通过 Seeker 软件实时在线观测待测对象运动情况，对反光标记点的三维空间位置进行记录，生成实时运动轨迹，并支持三维动态显示及捕捉数据的回放，便于对试验数据的调取及后期处理。该三维动作捕捉系统镜头分辨率为 20482048，像素可达 410 万，采样频率为 180Hz，完全满足本研究试验需求，整体装置布置及测试场地如图 2.3 所示。

引用格式 郭万朋.多环境蛇运动接触分析及其鳞片摩擦性能测试研究[D].长春理工大学，2021.DOI：10.26977/d.cnki.gccgc.2021.000653.

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多维弹力带抗阻训练对跳远运动员下肢爆发力影响效果的研究 ——以男子跳远二级运动员为例

关键词

多维弹力带；抗阻训练；跳远；下肢爆发力

摘要

下肢爆发力是跳远运动员需具备的重要素质之一,是运动员取得优异成绩的关键因素。下肢爆发力的训练手段形式多样,而传统的杠铃负重训练、快速伸缩复合训练在提高下肢爆发力方面仍然存在局限。因此,本文以提高运动员下肢爆发力为研究目的,以多维弹力带抗阻训练为干预手段,针对跳远专项的一般运动规律与特点,制定相应的下肢爆发力训练计划。采用专项成绩、身体素质以及运动生物力学参数对实验结果进行分析,讨论多维弹力带抗阻训练对男子跳远二级运动员下肢爆发力的影响效果,这不仅能丰富跳远项目下肢爆发力的训练手段,更能提升相关的理论水平。本文采用文献资料法、数理统计法、专家访谈法、问卷调查法与实验法；以多维弹力带抗阻训练对男子二级运动员下肢爆发力的影响为研究对象,以广州体育学院男子跳远二级运动员为实验对象。对运动员进行 8 周的多维弹力带抗阻训练干预,对比分析跳远运动员在实验前后的专项成绩、身体素质、运动学与动力学数据,研究结果显示: (1) 干预前运动员的专项平均成绩为 5.85m,干预后平均成绩为 6.07m,提高了 0.22m,具有非常显著性差异（$P < 0.01$）。（2）与干预前相比,运动员的 60 米计时跑和闭眼左腿站立无显著性差异（$P > 0.05$）；叉腰纵跳、纵跳、立定跳远、浅蹲最大重量、后抛实心球、1 分钟两头起、闭眼右腿站立均具有非常显著性差异（$P < 0.01$）；闭眼左腿站立具有显著性差异（$P < 0.05$）。（3）与干预前对比,运动员起跳过程的运动生物力学参数均有变化:运动员的起跳时间减短、扇面角减小与蹬地角减小,起跳阶段着地角增大,其中运动员起跳阶段起跳腿角度更接近于高水平运动员,踏跳阶段地面反弹力平均提高了 0.38 倍。结论: (1) 多维弹力带抗阻训练融入到跳远运动员的下肢爆发力训练中,对运动员的专项成绩与身体素质均有提高,该训练对运动员的下肢爆发力有促进作用。（2）干预后,运动员的运动学指标与动力学指标均有不同程度的变化,更趋向于优秀运动员。表明通过多维弹力带抗阻训练提高了其下肢爆发力,使其跳远技术动作得到优化,为取得更好成绩奠定基础。

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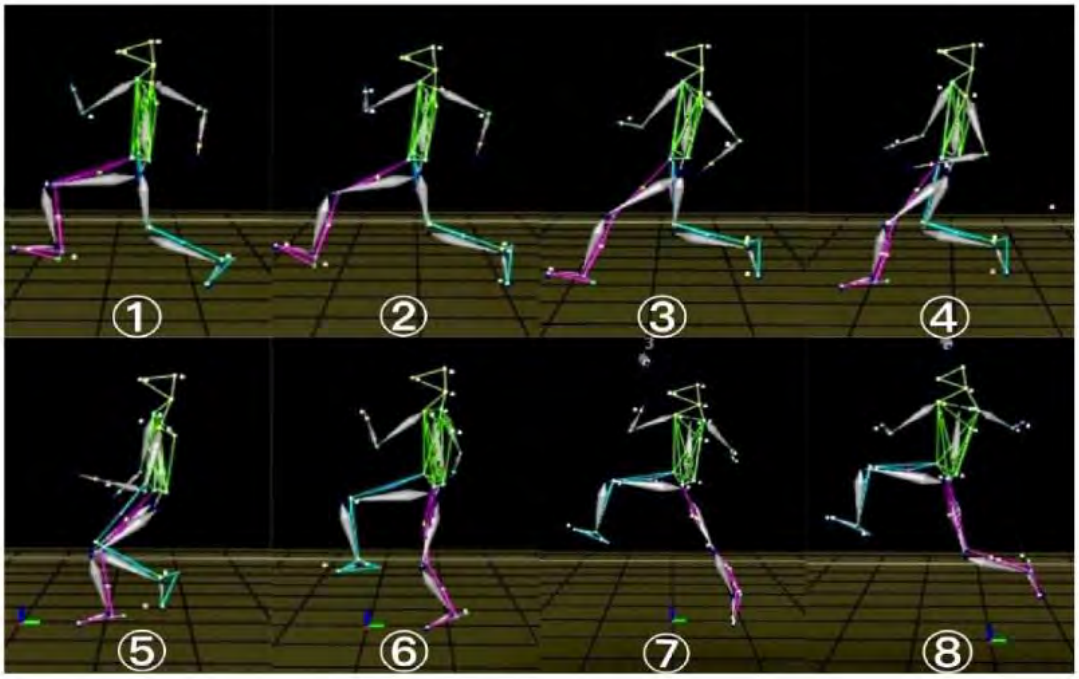

图 7 起跳技术动作特征画面示意图

引用格式 邹新貌.多维弹力带抗阻训练对跳远运动员下肢爆发力影响效果的研究[D].广州体育学院，2022.DOI：10.27042/d.cnki.ggztc.2022.000098.

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非对称联合运动中共同表征的认知神经机制

关键词

联合运动；计划协调；共同表征；超扫描技术

摘要

日常生活中个体之间的联合运动无处不在。联合运动是指两个或两个以上个体在空间及时间上的运动协调，以实现社会互动（Sebanz,Bekkering, & Knoblich，2006）。根据个体间任务的难易程度，将个体间任务难度一致的联合运动称为对称性联合运动，例如联合 Simon 任务；将个体间任务难度不一致的联合运动称之为非对称联合运动。然而，无论是对称性联合运动还是非对称联合运动都伴随着个体间的计划协调，即联合运动中的个体为了完成共同目标而采取的行动。以往在对称性联合运动任务中发现，个体与他人的计划协调往往伴随着个体间的共同表征。因此，探究共同表征的认知神经机制对今后个体间协同活动的干预提供了理论及实证基础。前人在对称性联合运动的基础上提出关于共同表征内容的两种观点，一是动作共同表征，二是任务共同表征。然而，该任务下行动者与共同行动者往往存在着反应选择的冲突。个体必须对他人任务或反应进行加工以保证共同目标的成功完成。在此基础上获得的共同表征效应很有可能是因任务的刺激 - 反应模式所诱发，而非计划协调所致。另外，个体对他人任务或反应的表征大部分都是通过对他人的视觉观察（知觉）来完成的。然而，他人的任务信息也可以通过线索提示（表象）的方式告知给行动者。因此，线索提示是否同视觉观察一样，能够引起个体间的共同表征，这也是本研究主要探索的问题之一。

目前大部分研究都是基于孤立范式下考察个体间的共同表征对其自身大脑激活模式的影响。但行为的同步与脑间神经活动的同步密切相关。共同表征效应下个体之间的神经活动会发生与之对应的知觉、运动及认知耦合。为了揭示共同表征下个体间内在耦合的神经基础，需要我们在双脑的角度上对其进行进一步的解读。

为了解决上述问题，本研究引入了一种非对称联合运动任务。在该任务下个体不对他人的任务或动作进行加工仍可完成联合运动。本研究在该任务的基础上，系统性的探讨了个体间共同表征的认知神经机制。我们操纵了共同行动者的刺激特征、运动特征、行动者的运动方向、视觉观察及线索提示等变量，通过三项研究五项实验展开对上述问题的探讨。

研究一的目的是通过运动捕捉系统探讨视觉观察情境下共同行动者是否影响行动者的运动表现，及其原因。实验 1a 在非对称联合运动任务中考察个体间的共同表征效应是否发生。该实验选取 21 对被试，在 2（遮挡：有，无）X 2（障碍物：有，无）被试内实验设计下考察非对称联合运动任务中共同行动者对行动者运动表现的影响。结果发现行动者的最大运动高度受共同行动者的影响，发生了共同表征效应。实验 1b 是在实验 1a 的基础上改变了行动者的运动方向，选取 18 对被试，考察该效应的稳定性。结果显示，该效应不因个体间运动方向的变化而变化。

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实验 2a 和实验 2b 分别控制了共同行动者的刺激特征和运动特征，以确定个体间共同表征的内容。其中实验 2a 采用了单因素三水平（障碍物：0cm，20cm，30cm）被试内实验设计，且要求其执行任务时最大运动高度超过 23cm；实验 2b 在实验 2a 的基础上保留了无障碍物条件及 20cm 障碍物条件，并调整了共同行动者的运动特征，要求其触及远处目标点时的最大运动高度超过 23cm，触及近处目标点时超过 33cm。实验 2a 和实验 2 b 各选取 19 对被试。结果发现，行动者对共同行动者任务内的障碍物特征进行了表征，支持了任务共同表征观点。以上两个实验的结果说明，在非对称联合运动任务中，行动者对共同行动者的视觉观察引起其对他人任务内刺激特征的加工，发生了共同表征效应，且该效应不受个体运动方向的影响。

研究二的目的是通过运动捕捉系统探讨在无视觉观察情境下，线索提示能否在非对称联合运动任务中引起个体间的共同表征效应。其中实验 3a 旨在探讨这种情境下线索提示对个体间共同表征的影响。选取了 21 对被试，采用 2（线索：有，无）X 2（障碍物：有，无）被试内实验设计。结果发现相比于无线索条件，线索提示后共同行动者任务中的障碍物影响行动者的最大运动高度。实验 3b 在。实验 3a 的基础上，改变行动者的运动方向，来考察这种基于线索提示的共同表征效应的稳定性。18 对被试的结果显示，该效应不因个体间运动方向的不一致而消失。研究二的结果表明，线索提示能够引起个体间的任务共同表征，且该效应稳定。

研究三借助基于沉 IRS 的超扫描技术探讨非对称联合运动任务中个体间共同表征的神经基础。实验 4 旨在考察视觉观察情境下个体间共同表征的神经基础。实验 5 的侧重点则在于线索提示下共同表征的神经机制。对行动者单脑分析的结果发现，在视觉观察情境下，行动者的颞顶联合区在他人有障碍物条件下的激活水平显著高于他人无障碍物条件；在线索提示条件下，行动者的颞顶联合区在他人有障碍物条件下的激活水平也显著高于他人无障碍物条件。对 18 对被试双脑分析的结果显示，相比于无视觉观察情境，视觉观察及线索提示情境下个体间运动计划相关脑区（行动者的前运动和辅助运动皮层与共同行动者的背外侧前额叶）的同步性活动增强；且相比于线索提示，视觉观察情境下行动者的额下回与共同行动者颞顶联合区的脑间同步性增强。以上两个实验结果说明行动者的颞顶联合区与非对称联合运动中的共同表征效应有关。个体间运动计划相关脑区上神经活动的同步性增强可能是非对称联合运动任务内个体间共同表征的神经基础。行动者的运动观察与共同行动者的自我任务加工相关脑区的脑间同步性增强是基于视觉观察的共同表征所特有的。

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运动捕捉系统。采用北京度量科技生产的 Nokov 光学三维运动捕捉系统（Mars4H，NokovCorporation，Beijing，China），来追踪被试的运云力轨迹。在木棒的顶端和中间分别固定好一个反光标示点，并使用 8 个高功率的 HLED 发光器来捕捉木棒（标示点）运动时的三维坐标及跨越障碍物的情况。该设备的采样率为 100 Hz。

引用格式 张琪涵.非对称联合运动中共同表征的认知神经机制[D].天津师范大学,2019.

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高低帮篮球鞋对运动员下肢生物力学特征的影响研究

关键词

高低帮篮球鞋；慢性踝关节不稳；生物力学特征；球鞋设计；稳定性

摘要

篮球鞋的高帮设计是为了提高运动员踝关节处的抗扭伤能力。本文选取 30 名试验对象，其中踝关节正常者 15 人，因扭伤罹患慢性踝关节不稳定者 15 人，对同一品牌、同一系列高低帮篮球鞋对运动员下肢生物力学的影响进行分析。选择篮球运动中对踝关节压力最高的侧切变向动作为例进行下肢动作捕捉，并采用测力台收集试验对象在开展这一动作前中后期踝关节力学参数。试验结果表明：在 30 名试验对象中，正常者和慢性踝关节不稳定者均能够通过高帮设计提高自身踝关节处的侧向稳定性，降低因变向、侧切等技战术动作带来的扭伤风险。

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1. 4 数据采集与处理
运动员下肢部分的生物力学参数主要通过 8 组红外高速动作捕捉 系 统 实 现。 本文选择的动作捕捉系统为 Nokov 系列光学动作捕捉系统，该系统能够实现亚毫米精度的全身运动捕捉系统，可以同时对运动员下肢各部位快速实时动作捕捉，测试标记点主要包括左右外踝点、左右内踝点、左右鞋后跟点、左右鞋尖点等，主要采集运动员变向时触地时的踝关节内外翻角度、角速度，缓冲阶段运动员的最大踝关节内外翻角度、角速度，最大踝关节内外翻幅度，最大踝关节内外翻力矩等；测力台则主要负责收集运动员蹬地时的地面反作用力数据，包括向后的地面反作用力、向 内的地面反作用力，以及最大垂直地面反作用力等。

引用格式 赵永刚,李岳霖.高低帮篮球鞋对运动员下肢生物力学特征的影响研究[J].中国皮革,2022,51(07):89-93.DOI:10.13536/j.cnki.issn1001-6813.2022-007-020.

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高职学前教育专业“项目式”舞蹈教学实践研究

关键词

高职学前教育；园校融合；学前教育专业；“项目式”舞蹈教学

摘要

文章紧密结合幼儿园实际需要,从高职学前教育专业学生从业角度出发,分析目前学前教育专业高职舞蹈教学存在的问题。依据园校融合理念,通过全学段贯穿“项目式”舞蹈教学,科学优化学前教育专业舞蹈课程,探索“项目式”舞蹈教学园校融合的实施路径，有效推进学前教育专业舞蹈教学与幼儿园教学活动的融合，发挥艺术教育在幼儿教育中的积极作用，提高学生在幼儿园教育实践中的综合应用能力,体现“能力本位、园校融合、工学一体”的指导思想，实现高校教学与幼儿园用人的无缝对接。

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我们在单一动作较难掌握的情况下，运用 NOKOV 动画仿真模拟直观演示动作。学生在观看仿真动画视频时，主动发现自己动作问题所在，及时改错纠正。

引用格式 郭婷婷.高职学前教育专业“项目式”舞蹈教学实践研究[J].北京舞蹈学院学报,2022(01):124-131.

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功能性训练对背向滑步推铅球二级运动员最后用力技术影响的研究

关键词

功能性训练；最后用力技术；铅球运动；铅球二级运动

摘要

现阶段，体能训练是竞技体育领域研究的热点。功能性训练是体能训练中重要组成部分，已广泛应用在竞技体育领域。本研究针对背向滑步推铅球二级运动员存在的技术、身体功能障碍等问题，探索功能性训练对铅球最后用力技术的影响，目的是验证功能性训练对铅球最后用力技术是否有促进作用。本文通过文献资料法、专家访谈法、实验法和数理统计等研究方法，主要根据铅球二级运动员存在的问题及铅球最后用力技术动作，结合功能性训练的理念和训练方法，从而制定适合最后用力技术的功能性训练计划，并实施训练。通过分析实验前后运动员最后用力技术中各参数的变化，探讨功能性训练对最后用力技术的影响。旨在提高铅球二级运动员最后用力技术动作的合理性、实效性，最终达到提高运动成绩的目的，同时为铅球教学与训练提供科学合理的理论基础和实践意义。研究结果为：实验后，3 名运动员功能动作筛查测试结果整体得分提高了 2.67 分；最后用力技术中各指标趋于理想值，技术动作更加合理；运动员出手速度平均增加了 0.58m/s，出手角度和出手高度受自身条件的影响变化幅度不大，铅球成绩平均提高了 0.45m。

通过对研究结果的分析得出以下结论：

1、功能性训练是结合专项的综合训练或者组合训练，是各种训练方法的综合效果，与铅球最后用力技术特点相结合，两者都强调"运动链"、多关节多维度的动作练习及深层肌肉群的重要性等，通过功能性训练能够增加铅球最后用力技术动作效率和经济性，对整个铅球技术水平的提高具有直接帮助。

2、通过功能性训练，有效提升了铅球运动员完成专项技术动作所需要的身体稳定性、灵活性、上下肢协同配合能力及动作控制能力等。

3、功能性训练对铅球成绩的提高有显著性效果，对铅球最后用力技术有促进作用。最后用力技术中各指标趋于理想值，动作更加合理，且符合运动学规律。

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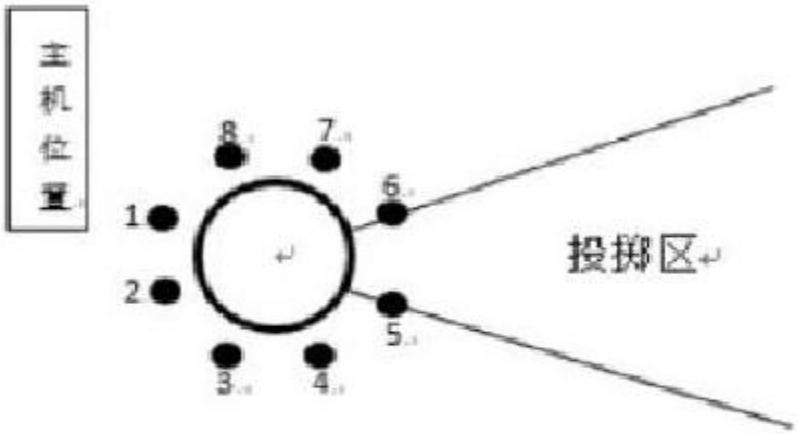

图 2 测试仪器位置示意图

NOKOV 度量动作捕捉在研究中的应用摘录

测试器材： FMS 测试仪、7.26kg 铅球、卷尺、 Nokov-Mars2H 三维动作捕捉系统。

训练仪器：弹力带、 Mini 带、绳梯、药球、栏架、瑞士球、杠铃、泡沫轴、花生球、体能垫、秒表。
实验前后用 Nokov-Mars2H 动作捕捉仪器对运动员推铅球的完整动作进行拍摄。为保证测量和 FMS 测试的准确有效性，测量时，测量人员为国家一级田径裁判员，严格按照 2018-2019 年田径竞赛规则，每名运动员轮流试投六次，每次间隔时间为 1.5 分钟进行测量。FMS 测试由经过具有 FMS 资格证书的专业人员测试，整个实验过程中在教练员的监控下完成的。
本文应用 Nokov-Mars2H 三维动作捕捉系统进行数据采集。拍摄频率为 100 帧/s，镜头高 2.5 米，8 个摄像镜头按照顺序放置在铅球场地周围（如图 2 所示），每个镜头距离投掷圈中心 5m。

引用格式 张甜.功能性训练对背向滑步推铅球二级运动员最后用力技术影响的研究[D].广州体育学院,2019.

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功能性训练对铅球运动员最后用力技术影响的研究

关键词

铅球：功能性训练：最后用力技术

摘要

功能性训练对铅球运动员在最后用力技术中的肌肉配合、动作练习，从训练理念及训练手段上都有高效契合的理念，本研究通 16 周的功能性训练，对 3 名二级铅球运动员在最后用力技术上的改变进行了运动学分析，通过运动员在身体活动链条上的各关节角度变化及试验前后的铅球出手数据指标对功能行训练对运动员最后用力技术的影响效果进行了分析。最后试验结果证明，3 名运动员在最后用力技术中的各项指标都出现了不同程度的改善，动作更加流畅合理，功能性训练在此起到了关键的作用。

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2.2 、研究方法
（ 1 ）影像拍摄法。
影像拍摄发法是本研究开展的重要基础， 由于运动员的最后用力阶段动作发展时间迅速，动作连贯性强，不适宜进行阶段性演示，因此需要运动员进行完整的动作演示，并根据影像的形式对动作进行记录以便进行详细的分析。 本研究的拍摄对象为表 1 中实验对象的推铅球动作，实验共进行 16 周，实验前后均采取同一台动作捕捉仪器进行拍摄（型号 Nokov-Mars2H）。所有运动员测试由同一名具有 FMS 资格证的专业人员进行，每人同一动作轮流拍摄 6 次，每次动作间隔 90s。

引用格式 冯杰.功能性训练对铅球运动员最后用力技术影响的研究[J].文体用品与科技,2022(19):77-79.

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攻球线路与性别对乒乓球专选大学生正手上旋技术动作运动生物力学特征的影响

关键词

乒乓球；正手上旋球；直线；中线；斜线；性别；运动学；动力学

摘要

研究目的：乒乓球运动是一项球速较快、线路落点旋转变化多、技巧性强的隔网对抗运动项目，正手攻球被认为是最有杀伤力的一种进攻方式，而上旋球是乒乓球中最重要的击球技术。不同性别运动员在身体形态、身体素质等方面存在差异，造成其所形成的打法与动作有所不同。在训练与比赛中采取不同攻球线路有助于形成不同的落点变化，使得对手无法预判落点，未能及时调整步法完成击球，一方面不易得分，另一方面易造成损伤，其中腰部与膝关节损伤最为常见。因此，本研究旨在探究攻球线路与性别对乒乓球专选大学生在正手上旋球动作运动生物力学特征的影响。研究结果可为乒乓球初学者、专选大学生以及教练员教学或训练提供实验支撑，同时可以为预防训练提供依据，为比赛中由于技术动作不规范而造成的运动损伤给予预防指导。

研究方法：本研究募集了太原理工大学体育学院 20 名乒乓球专选大学生进行测试，其中男女各 10 名。采用红外光点三维运动捕捉系统（Nokov，中国，200Hz）和三维测力台（Bertec，USA，1000Hz）采集受试者完成不同线路正手上旋动作时运动学与动力学数据。运用 Cortex642.6.2.1169 软件对运动学数据进行处理，关节三维力矩通过逆向动力学方法计算获得，关节力矩标准化为身高与体重乘积的倍数。通过 2×3 混合设计的双因素方差(Two-WayANOVA)分析性别与不同攻球线路对受试者上下肢运动生物力学特征的影响，如有交互作用，后续进行简单效应检验，采用单因素方差分析和独立样本 t-test 分别比较不同线路与性别间的差异。所有统计分析在 SPSS22.0 中完成，其中显著性标准误差概率小于 0.05。

研究结果：（1）双因素方差结果分析表明，不同线路和性别在挥拍击球时刻上下肢各关节角度上均存在交互（$p < 0.001$）。三种击球线路下，上下肢关节角度之间具有显著性差异。在挥拍击球时刻不同性别运动员在完成正手上旋击球动作直线与中线、斜线线路相比表现出较大的肩肘关节屈曲角（$p < 0.001$）及较小的肩肘关节内外旋角（$p < 0.001$），斜线与中线、直线线路相比表现出较大的下肢屈曲角（$p < 0.05$）及较小的内收外展角、内旋外旋角（$p < 0.05$）；不论线路，男性表现出较大的上下肢关节屈曲角及较小的内收外展、内旋外旋角（$p < 0.05$），而女性则表现出较大的肩关节内外旋角（$p < 0.001$）；（2）双因素方差结果分析表明，不同线路和性别在挥拍击球时刻肩关节、肘关节与踝关节各关节力矩、髋关节与膝关节屈伸力矩、内收外展力矩上均存在交互（$p < 0.001$）。三种击球线路下，上下肢关节力矩之间具有显著性。挥拍击球时刻不同性别运动员在完成正手上旋击球动作直线较中线与斜线线路表现出较大的肩肘关节屈伸和内收外展力矩（$p < 0.05$），斜线较中线与直线线路表现出较大的下肢屈伸力矩（$p < 0.05$），不论

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线路，男性均表现出较大的上下肢关节屈伸力矩（$p < 0.05$），较小的上肢内收外展、内旋外旋力矩（$p < 0.05$）。研究结论：（1）挥拍击球时刻，击打直线线路肘关节屈曲角大于斜线与中线线路，膝关节屈曲角较大，直线线路更依赖各关节屈伸力量，且不论线路男性上旋正手需要更多的下肢屈曲和旋转以及肩部屈曲和外展，女性更多使用肘部和肩部旋转。（2）中线可能是介于直线与中线间的一个调节线路，在训练中可以利用中线线路对直线与斜线线路进行训练，有助于更好的掌握技术动作。（3）斜线线路较中线与直线长，下肢蹬地发力需要更大的势能才能将球击出，更易造成下肢损伤风险。建议：迎球回击到直线线路，在击球过程中可以多注意上肢的屈伸，并且在球拍触球前适当的加大肩关节内收。将球回击到斜线线路时，可以多留意上肢关节的外旋。总之，发力的方向要跟击球落点方向一致。男性更加注重上肢小肌肉群的训练，上肢内收外展、内旋外旋肌肉的训练。女性更多的增加下肢力量、稳定性与协调性练习。

图2.2 -1　测试现场示意图

Figure 2.2-1　Test site diagram

NOKOV 度量动作捕捉在研究中的应用摘录

采用 12 镜头红外光点三维运动捕捉系统（ Nokov，中国）以 200Hz 的采集频率获取运动学数据，运用三维测力台（Bertec，美国）内置 2 块测力板，以 1000Hz 的采集频率获取动力学数据，实验设备包括 12 个红外镜头以及 1 台高速摄像机同步进行动作采集，每个受试者每个动作均采集 3 次有效数据，采集时间为 10s。实验测试地点在太原理工大学体育学院运动生物力学实验室进行，实验仪器及测试现场示意图（如图 2.2-1 所示）。

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惯性测量单元结合机器学习预测纵跳时下肢关节力矩

关键词

惯性测量单元；机器学习；纵跳；动力学；关节力矩

摘要

目的旨在利用惯性测量单元结合机器学习预测纵跳时的下肢关节力矩。方法光学红外动作捕捉系统、三维测力台与惯性传感器同步完成数据采集。随后，在 Visual 3D 软件中进行建模，并运用逆向动力学算法计算下肢三关节力矩。ML 模型在 Matlab 中建立，以 IMU 获取的四元素、加速度和角度等信息为特征向量，下肢关节力矩数据为输出目标值进行训练与预测。结果下蹲跳下肢矢状面关节力矩预测结果为：髋关节 CCF=0.960 4，RMSE=0.270 6，R2=0.920 4；膝关节 CCF=0.992 5，RMSE=0.181 7，R2=0.979 4；踝关节：CCF=0.965 3，RMSE=0.151 0，R2=0.910 9。蹲跳下肢矢状面关节力矩预测结果为：髋关节 CCF=0.921 7，RMSE=0.310 9，R2=0.825 1；膝关节 CCF=0.984 6，RMSE=0.232 4，R2=0.966 0；踝关节 CCF=0.919 3，RMSE=0.211 2，R2=0.825 7。结论单枚惯性测量单元结合机器学习的方法能够准确地预测下蹲跳和蹲跳下肢矢状面关节力矩，为监测运动训练、优化技术动作及预防运动损伤提供新方法与新思路。

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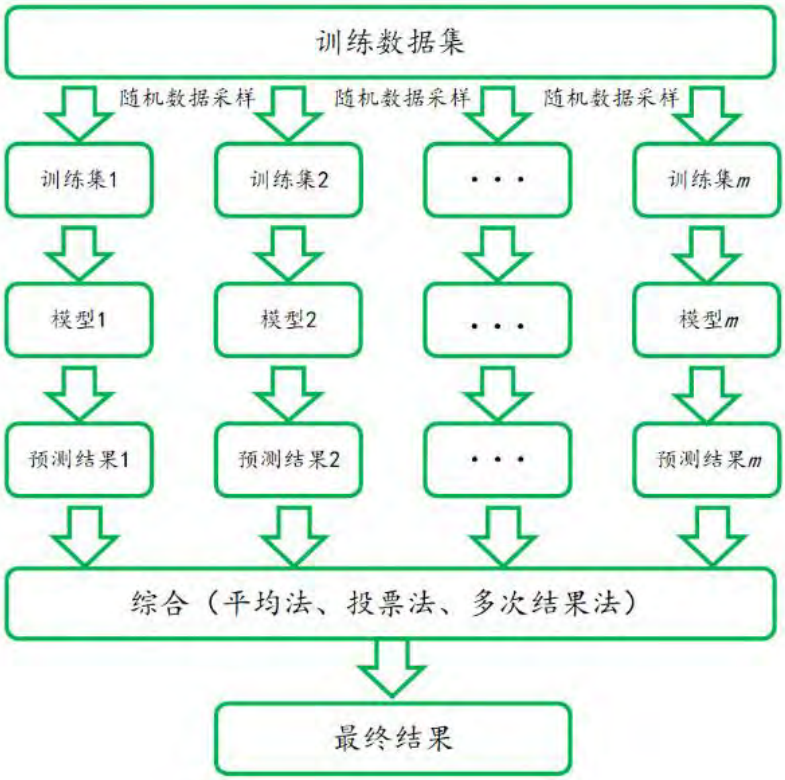

图 2　随机森林流程图

NOKOV 度量动作捕捉在研究中的应用摘录

受试者来到实验室后，先告知其实验流程，再测量记录年龄、身高、体重等基本参数，随后上跑步机自选速度热身 5 min。热身结束后，由操作人员指导受试者进行蹲跳和下蹲跳练习，使其快速熟悉动作模式。
实验开始前，为方便黏贴反光标记点，受试者需上身赤裸，下身穿着紧身裤。全身上下共黏贴 43 枚反光标记点与佩戴 2 枚 IMU（WT9011DCL，200 Hz），三维测力台放置于场地中央（Kistler，1 200 Hz），由周围 15 镜头的 NOKOV 光学三维动作捕捉系统（Mars 4H，240 Hz）完成数据采集工作

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核心动态稳定性训练对田径普修课推铅球教学效果影响的实验研究

关键词

核心动态稳定性训练；推铅球技术动作；推铅球成绩

摘要

背向滑步推铅球是技术相对较复杂的运动项目，要求运动员在投掷过程中保持重心的稳定和身体姿势的控制。核心动态稳定性训练作为体能训练的一种，能较全面的提升个体在运动中核心肌群的稳定能力和增加运动肌群的力量。本研究针对推铅球教学训练中易忽视的核心稳定性训练，探索核心动态稳定性训练对推铅球教学效果的影响，目的是验证核心动态稳定性训练对推铅球技术掌握和成绩的提高是否有促进作用。本文通过文献资料法、专家访谈法、实验法和数理统计法等研究方法。结合背向滑步推铅球项目的技术原理以及运动学规律，设计出一套核心动态稳定性训练方案，将其应用在推铅球技术教学课中，实验结束后，对实验对象推铅球成绩和动作技术进行考评并分析。同时为了更好的对教学效果进行检验，采用 Nokov-Mars2H 三维动作捕捉系统对实验对象进行运动学数据采集，对所获得的运动学数据进行对比分析。结果如下：1，专项素质与稳定性测试：实验前后实验组与对照组 30m 跑无显著性差异（$p > 0.05$），但立定跳远、原地推铅球、原地推实心球、一分钟仰卧起坐及 FMS 得分实验前后实验组提升幅度大于对照组（$p < 0.05$）。2，推铅球成绩和技评得分：实验后，实验组推铅球成绩平均值比对照组高 0.37m，差异显著（$p < 0.05$）。技术评分两组实验对象握持球和预备姿势无显著性差异（$p > 0.05$），滑步阶段、转换阶段、最后用力和维持平衡阶段得分实验组比对照组提升显著（$p < 0.05$）。3，运动学数据分析：实验验后实验组各阶段的关节角度变化更趋于理想值，重心水平速度实验组比对照组提高显著（$p < 0.05$），出手速度和出手角度更符合技术要求。出手高度两组实验对象平均值无差异（$p > 0.05$）。通过分析得出以下结论：1，通过核心动态稳定性训练，可以促进学生专项素质提升，能有效提升核心力量，提高推铅球出手力量，加快动作速度，保证动作技术的连贯性。2，核心动态稳定性训练对推铅球成绩提高有较好帮助，试验后实验组学生铅球平均成绩更优。3，在滑步阶段，实验组学生重心水平速度较快，左腿摆动较积极，重心起伏程度较低，滑步时间较短，滑步距离较大。整个滑步技术更符合教学要求。4，在过渡阶段，对照组学生左腿下落较慢，建立起稳定的双支撑平面效果较差，对照组学生右髋上抬幅度值较大，左侧支撑技术不理想，右腿下落时右踝角度较大，没有在右腿落地时迅速的内扣及蹬伸，导致过渡阶段的水平速度损失较大。5，在最后用力阶段，实验组学生铅球速度与重心速度差值小于对照组，“人-球”整体效果更好，实验组学生出手速度和出手角度更符合教学技术要求，各项指标更趋于理想效果。

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图 1

NOKOV 度量动作捕捉在研究中的应用摘录

本文使用三维动作捕捉系统（ Nokov-Mars2H，中国）对实验对象进行运动学数据采集。设备详情见图。
评价滑步阶段动作速度指标有两个：一为右腿蹬离地面时的水平方向速度要尽可能的大，二为右腿蹬离地面时在垂直方向的速度要尽可能的小\[75]。相关研究表明：我国优秀铅球运动员李梅素滑步阶段水平速度达到了 2.221m/s，垂直速度仅 0.533m/s。而本文所用 Nokov-Mars2H 三维动作捕捉系统能有效捕捉三个轴方向的速度值（见图 2）。其中 x 轴（左右方向速度）与本研究无关，故并未统计。实验对象在滑步阶段重心速度统计见表 14。

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护踝对 FAI 患者踝关节扭伤高危动作运动生物力学的影响

关键词

FAI 者；半刚性护踝；弹性护踝；高危动作；踝关节扭伤；下肢着地策略；

摘要

研究目的:踝关节扭伤是体育运动中最常见的下肢损伤之一,其中外侧踝关节扭伤尤为突出,其主要是由于踝关节被迫内翻和跖屈所致。研究得出约有 40%-75%的外侧踝关节扭伤患者会进一步发展为慢性踝关节不稳者。Hertel 等人则进一步将由于本体感觉或神经肌肉缺陷导致的复发性踝关节不稳人群,定义为功能性踝关节不稳定者（Functional Ankle Instability,FAI）,踝关节"失控感"对运动中姿势控制会产生负面影响。大量文献已证实,佩戴护踝对减少 FAI 者踝关节扭伤是有效的。当前常用的护踝类型包括弹性护踝、半刚性护踝和刚性护踝。已有学者指出护踝会改变着地动作的神经肌肉控制,然而护踝对一些指标的影响以及不同护踝的防护效果存在争议。本研究以 FAI 者为研究对象,探讨不同护踝对 FAI 者踝关节损伤高危动作着地动作策略的影响,以期更全面了解护踝的保护机制。

研究方法:选取 10 名 FAI 者为受试者,选用半刚性和弹性护踝。半刚性护踝为使用半刚性夹板对踝关节两侧进行支撑的护踝,具体为 Active ankle T2 支撑护踝（Cramer,美国）。弹性护踝为使用八字绷带或其他弹性材料对踝关节进行牵拉保护的护踝,选用 195 型护踝（McDavid,美国）。FAI 者随机佩戴半刚性护踝、弹性护踝及无护踝状态下进行急停侧切、急停起跳落地和跳箱单脚落地动作。运用红外光点运动捕捉系统（Nokov Mars2H）和三维测力台（Bertec）获得受试者运动学和动力学数据。采用 3×3 重复设计的双因素方差分析验证护踝和动作对 FAI 者下肢运动生物力学特征的影响。

研究结果:双因素方差结果显示,动作和护踝对踝关节矢状面 ROM（F\[1,4]=11.82,P < 0.001）和额状面 ROM（F\[1,4]=41.78,P < 0.001）有显著性交互作用。单因素方差分析结果表明,不论护踝,在着地时刻,侧切动作的踝关节内翻角较急停（-5.4°vs.4.5°,P < 0.001）和落地动作小（-5.4°vs.7.9° P < 0.001）,且急停时的内翻角小于落地动作（4.5°vs.7.9°,P < 0.001）。除此之外,落地时的踝关节背屈峰值小于急停（-54.5°vs.-86.8°,P=0.05）。与侧切相比,急停时踝关节背屈最大时刻的内翻角更大（9.9°vs.7.2°,P=0.05）。不论动作,弹性护踝可以显著降低踝关节背屈峰值（12%,P=0.031）。在着地时刻,半刚性护踝可以显著减小踝关节内翻角（78%,P=0.029）。踝关节背屈最大时刻,半刚性护踝（52%,P < 0.001）和弹性护踝（40%,P < 0.001）可使踝关节内翻角降低。侧切动作中,半刚性护踝减小了踝关节矢状面（40%,P=0.047）和额状面（41%,P=0.018）ROM。急停动作下,半刚性护踝降低踝关节矢状面 ROM（37%,P=0.008）。落地动作中,半刚性护踝（19%,P=0.014）和弹性护踝（19%,P=0.017）均对踝关节额状面 ROM 有减小作用。不论护踝,落地时前后和垂直方向的 GRF 大于侧切（0.8BW vs.0.5BW,P=0.043）和急停（0.8BW vs.0.3BW,P=0.005）。除此

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之外,落地动作的前后方向 TTP 比侧切、急停更短（40ms vs.222ms vs.225ms,P < 0.001）。侧切和落地动作的内外方向 TTP 快于急停（65ms vs.39ms vs.105ms,P < 0.001）。与侧切（80ms vs.41ms,P=0.017）和急停（98ms vs.41ms,P < 0.001）相比,落地动作的垂直方向 TTP 更短。不论动作,与空白组相比,弹性护踝延长了垂直方向的 TTP（28%,P=0.049）。

研究结论:与无护踝相比,半刚性护踝通过限制着地时刻和踝关节背屈最大时刻的踝关节内翻,减小踝关节矢状面和额状面的关节活动度等落地策略,降低了踝关节不稳者在落地动作时发生外侧踝关节扭伤的风险。弹性护踝能够限制踝关节背屈和踝关节额状面关节活动度,降低垂直方向的负荷率,进而发挥弹性护踝对 FAI 者的防护机制。整体看来半刚性护踝的防护效果可能更为显著和全面。此外,本研究还发现不论何种护踝下,与侧切和急停起跳动作相比,跳箱单脚落地动作下由于落地时踝关节内翻角更大、背屈减小、踝关节 ROM 大、地面反作用力更大、增大了踝关节负荷率等特征,使 FAI 者在跳箱单脚落地动作下更倾向于引起踝关节损伤。建议:FAI 者在佩戴护踝后的运动策略与无护踝相比发生了变化,特别是佩戴半刚性护踝后重点改善了落地时刻的运动学特征,但是对动力学参数的影响有限。因此建议 FAI 者注重锻炼下肢肌肉力量,在发生损伤的高危动作时,能够很好地进行应对,减小踝关节损伤风险。

NOKOV 度量动作捕捉在研究中的应用摘录

FAI 者随机佩戴半刚性护踝、弹性护踝及无护踝状态下进行急停侧切、急停起跳落地和跳箱单脚落地动作。运用红外光点运动捕捉系统（ NokovMars2H）和三维测力台（Bertec）获得受试者运动学和动力学数据。采用 3×3 重复设计的双因素方差分析验证护踝和动作对 FAI 者下肢运动生物力学特征的影响。

引用格式 张美珍,张泽毅,尹彦等. 护踝对 FAI 患者踝关节扭伤高危动作运动生物力学的影响[A]. 中国体育科学学会.第十二届全国体育科学大会论文摘要汇编——专题报告（运动生物力学分会）[C].中国体育科学学会：中国体育科学学会，2022：2.DOI：10.26914/c.cnkihy.2022.004231.

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护踝对功能性踝关节不稳患者下肢运动生物力学特征的影响

关键词

半刚性护踝；弹性护踝；步行；跑步；运动生物力学；能量吸收

摘要

目的 探究护踝对功能性踝关节不稳（functional ankle instability，FAI）患者的保护作用，为其护踝的选择提供依据。方法 15 名 FAI 患者随机佩戴半刚性、弹性护踝及无护踝以自选速度步行和跑步，运用红外光点运动捕捉系统和三维测力台采集其下肢运动生物力学参数。通过 3×2 重复设计的双因素方差分析检验护踝和运动模式对下肢运动学、动力学和能量吸收的影响。结果 护踝与运动模式对本研究中所有指标均无交互作用(P>0.05)。不论运动模式，与无护踝相比，弹性护踝显著减少了 FAI 患者踝关节内翻角峰值（P<0.001）、内翻角速度（P=0.036）和踝关节能量吸收（P=0.03），同时增加了踝关节外翻力矩（P<0.001）；而半刚性护踝增加了踝关节内翻角峰值（P=0.004）和内翻角速度（P<0.001）。此外，弹性护踝可降低着地时刻的膝关节内旋力矩（P=0.035）和外旋力矩峰值（P<0.001）。结论 与无护踝相比，弹性护踝通过减小踝关节内翻角、内翻角速度和能量吸收，增大踝关节外翻力矩，继而起到预防踝关节扭伤的作用。FAI 患者佩戴半刚性护踝后需定时关注踝关节慢性损伤风险。整体来看，弹性护踝的防护效果可能更有效，且未引起膝关节功能补偿，可作为预防 FAI 患者踝关节扭伤的有效措施。

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NOKOV 度量动作捕捉在研究中的应用摘录

所有受试者分别在佩戴半刚性、弹性护踝和无护踝状态下以自选速度完成步行和跑步测试。 对护踝和运动模式的测试顺序设置不同编号， 利用随机数生成器设计出随机顺序（见图 1）。运用 12 镜头红外光点三维运动捕捉系统（200 Hz，Nokov Mars2H，北京度量科技有限公司）及三维测力台（1 kHz，Betec 公司，美国）同步采集运动学和动力学数据。每名受试者每个动作均采集 3 次有效数据。

引用格式 杨亦敏，张泽毅，刘卉等.护踝对功能性踝关节不稳患者下肢运动生物力学特征的影响[J].医用生物力学，2023,38（04）：742-748.DOI：10.16156/j.1004-7220.2023.04.016.

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护踝对篮球运动员 FAI 和 Coper 患者下肢运动生物力学的影响

关键词

FAI 者；Coper 患者；护踝；高危动作；踝关节扭伤

摘要

研究目的：踝关节扭伤在篮球运动中极为多见，常发生于急停侧切、急停起跳和单腿落地动作。据报道，一些篮球运动员在多次扭伤后出现踝关节"失控感"，进而形成了功能性踝关节不稳（Functional ankle instability，FAI）。也有部分运动员在初次扭伤后，暂时没有出现再次扭伤情况，这种人群为 Coper 患者。但 Coper 患者的距腓前韧带较健康人群更松弛，也会增大踝关节扭伤风险。护踝已被证明是目前预防踝关节扭伤最为常用和有效的手段之一，但护踝对 FAI 和 Coper 患者的保护机制还不清晰。因此，本研究通过分析护踝对篮球运动员 FAI、Coper 患者在踝关节扭伤高危动作下下肢运动生物力学的影响，尝试为 FAI、Coper 患者护踝的选择提供依据和建议。

研究方法：分别招募 FAI 者、Coper 患者和健康人群各 10 名，通过红外光点运动捕捉系统（Nokov Mars2H）和三维测力台（Bertec）采集受试者佩戴不同类型护踝完成急停侧切、急停起跳、单腿落地时的下肢运动生物力学参数。采用 3×3×3 混合设计的三因素方差分析验证动作、人群和护踝对下肢运动生物力学参数的影响。若因素间存在显著性交互作用，则通过单因素方差分析分别比较人群、动作、护踝间是否存在显著性差异，主效应差异采用 Bonferroni 进行校正。运用统计参数映射进一步确定自变量对因变量影响的时间范围。

研究结果：1）比较 FAI、Coper 患者和健康人群下肢运动模式发现：急停侧切 68%\~82% 动作周期中 FAI 患者表现出更大的踝关节内翻角速度（P=0.011）、膝关节矢状面 ROM（36.0°vs. 29.4°vs.24.3°，P=0.05）、膝关节能量吸收（-4.7J vs. -2.9J，P=0.049）。单腿落地时 FAI 患者的踝关节矢状面 ROM 较 Coper 和健康人群更大（51.1°vs.34.2°vs.37.3°，P < 0.05），踝关节能量吸收也有增加的趋势（-1.9Jvs.-1.1J，P=0.11）。除此之外，单腿落地 8%\~16% 动作周期中 Coper 患者的垂直 GRF 显著低于 FAI 患者和健康人群（P < 0.05）。2）分析不同护踝在不同动作下的保护效果得出：不论动作，弹性护踝可以显著降低踝关节背屈峰值（12%，P=0.031），延长垂直方向的 TTP（28%，P=0.049）。此外，半刚性护踝（52%，P < 0.001）和弹性护踝（40%，P < 0.001）均可以限制踝关节内翻角。关节活动度方面，半刚性护踝减小了急停侧切时的踝关节矢状面（40%，P=0.047）和额状面（41%，P=0.018）ROM，降低了急停起跳时的踝关节矢状面 ROM（37%，P=0.008）以及单腿落地时的踝关节额状面 ROM（19%，P=0.014）。而弹性护踝对急停侧切（41%，P=0.018）和单腿落地时（19%，P=0.017）的额状面 ROM 有显著限制作用。3）进一步探索不同护踝对不同人群的保护效果发现：对于 FAI 者，弹性护踝降低了急停

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侧切和急停起跳时的踝关节跖屈角（2.8°，P=0.047）。半刚性护踝（4.2°。P=0.033）和弹性护踝(5.4°, P=0.006)均对踝关节矢状面 ROM 有限制作用。对于 Coper 患者，半刚性护踝(2.6°，P < 0.001）和弹性护踝（2.1°，P=0.002）均降低了膝关节额状面 ROM。此外，半刚性护踝还减小了踝关节额状面 ROM (2.6°, P=0.046)，膝关节 (0.027J/kg, P=0.048) 和踝关节 (0.055J/kg，P=0.013）的额状面能量吸收，提升了踝关节额状面稳定性（0.25vs.0.29，P=0.05）。对于健康人群而言，半刚性护踝（3.7°，P=0.05）和弹性护踝（5.9°，P=0.003）均减小了踝关节矢状面 ROM。半刚性护踝还降低了踝关节矢状面能量吸收（0.158J/kg，P=0.046）

研究结论：对于 FAI 者和健康人群，半刚性护踝和弹性护踝均起到降低踝关节扭伤风险的作用。半刚性护踝还可以降低踝关节在下肢关节中的能量吸收比重，因此提示，半刚性护踝的保护机制更为全面。对于 Coper 患者，半刚性护踝可以通过踝关节内翻和额状面能量吸收来保护踝关节，并由此产生了一些膝关节代偿反应，如膝关节额状面能量吸收减小，有助于降低膝关节额状面负荷。所以提示，FAI、Coper 患者和健康人群在篮球运动中更适合佩戴半刚性护踝，特别是有膝关节损伤史的 Coper 患者。需注意，所有护踝均不会影响急停侧切和急停起跳时的运动表现。

NOKOV 度量动作捕捉在研究中的应用摘录

2.3 数据采集
运用 12 镜头红外光点运动捕捉系统（ Nokov Mars2H，中国）以 200Hz 的采集频率获得受试者急停侧切、急停起跳、单腿落地的运动学数据。同时使用 Bertec（美国）三维测力台通过同步采集卡连接红外镜头， 对受试者下肢动力学数据进行同步采集，采样频率为 1000Hz。每名受试者每个动作均采集 3 次有效数据。

引用格式 张泽毅. 护踝对篮球运动员 FAI 和 Coper 患者下肢运动生物力学的影响[D].太原理工大学,2022.DOI:10.27352/d.cnki.gylgu.2022.000659.

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滑雪运动员姿态准确捕捉系统的研究与设计

关键词

人体姿态捕捉；ZigBee 网络；惯性系统；数据融合；虚拟现实

摘要

滑雪运动是一项很好的冬季运动项目。随着我国国民经济的快速发展，尤其是 2022 年冬季奥运会的申办成功，国家对该项运动的重视程度非常高，越来越多的人投入到冰雪运动中。准确捕捉滑雪运动员关节点的姿态信息，为正确指导学员学习提供数字化的支撑，对提高学习效率意义重大。随着科学技术的进步，人体姿态捕捉技术越来越多的应用在体育运动中，如篮球、游泳、体操等体育项目。目前光学摄像头和惯性传感器已经成为采集人体姿态的两种主要方式，然而这两种方式依然存在许多问题，传感器方面由于滑雪运动员运动快速且复杂，容易造成对人体姿态捕捉不准确的问题，光学方面主要是对采集环境要求高，滑雪运动员在运动过程中容易发生遮挡，会造成采集人体姿态不准确。

本文依托于吉林省教育"十三五"科学技术研究规划项目，项目名称"多特征信息融合技术在滑雪教学中的应用研究"，开展信息技术在滑雪运动中的研究与设计。为了提高滑雪运动员姿态捕捉的准确度，本文设计了一种将惯性传感器与光学摄像头数据相融合的姿态识别系统，本系统分为下位机硬件与上位机软件两个部分。首先惯性采集部分，将 11 个采集节点佩戴在滑雪运动员主要关节点附近，模块使用 ZigBee 协议以无线的方式进行数据的采集与发送，更加便捷与经济，降低对滑雪运动员做动作时的影响。其次本文利用多线程的方式，分别在时间和空间上进行变换计算，对惯性传感器和光学摄像头的数据进行融合，提高滑雪运动员姿态捕捉精度。最后在上位机建立了人体模型，通过 Unity3D 对滑雪运动进行实时展示，将学员姿态与教练员进行对比，直观的找出其存在的问题，提供一个可视化的教学方法，极大提高教学效率。

通过硬件电路的设计与软件功能的开发，实现了一个具有无线传输功能以及将传感器与摄像头有效结合起来的人体姿态识别系统。经过测试系统操作简单、结构稳定且功能全面，能够达到预期人体姿态采集效果，对滑雪运动提供给了一个全新的数字化和可视化的教学工具，还可以运用到其它多个方面，具有很好的应用前景。

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图 3-6 Mars2H 摄像头

Figure 3-6 Mars2h camera

NOKOV 度量动作捕捉在研究中的应用摘录

本文采用的光学摄像头是三维红外被动式摄像头（ NOKOV），系统选用 12 个光学摄像头、 L 型标杆、T 型标杆、Marker 反光球、三向云台、三角支架和交换机（ A、B）等组成。本文所采用的 NOKOV 摄像头为 Mars2H 型号，如图 3-6 所示。Mars2H 型号摄像头采用了技术先进的捕捉技术，为姿态采集提供了可靠的数据支持，可以实时的捕捉到人体运动过程中的每一个姿态，并且直接通过以太网传输给上位机，方便快捷。摄像头通过与它相连的网线进行供电，摄像头的具体参数如表 3-4 所示。

硬件设备中 L 型标定杆主要是用来确定摄像头系统中的坐标轴和正方向， 本实验中采用软标定，较长的边为 x 轴的正方向，较短的为 y 轴正方向，支持右手定则，选取向上为 z 轴的正方向；T 型标定杆是在进行完成 L 型标定后， 一人拿着 T 型杆在采集区域内挥舞，尽量达到采集区域的所有地方，此后上位机进行计算，若所得校准杆长度和实际的长度一致就可以通过，还能够看到实际的丢点率，若校准长度和实际长度不一致，则需要重新标定； NOKOV 光学三维动态捕捉采用的是被动式光学原理，使用时需要在被捕捉人体上粘贴表面涂有反光材料的 Marker 小球，反光小球具有反光率高等特点，在使用时候不需要任何电缆连接、不发光、无辐射、不易损坏，非常方便使用。

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基于 IMU 的膝关节转角测量及在康复训练中的应用研究

关键词

膝关节角度；IMU 组合布局；膝关节康复评价；传感器融合

摘要

随着老龄化程度逐渐加深,人们对全膝关节置换术后的康复训练需求逐步提升。针对术后患者因康复评价不及时或康复机器人机构设计不完备,导致的康复效果不显著等问题,本文以提高膝关节角度测量的准确性为目标,提出了一种结合人体运动学约束和最优惯性传感器(Inertial Measurement Unit,IMU)组合布局的膝关节角度测量方案,并对其开展研究:根据膝关节运动过程中固有约束建立膝关节简化模型,通过模型解算得到两个传感器与膝关节轴的位姿关系,并解决其运算过程中的关节轴符号配对问题,实现了 IMU 与膝关节的实时校准。然后基于 IMU 实时采集的角速度和加速度数据,通过角速度积分和加速度投影的方式分别计算矢状面内的膝关节角度。最后基于自适应卡尔曼滤波的数据融合方法将这两种解算方式的优势有效结合,从而确定了关节角度测量方案。针对该方案存在不可避免的皮肤运动伪影问题,根据康复训练过程中机器人与患者的实际情况,筛选海伦海叶丝标记位置等权威标志点。接着将皮肤运动较小的有效标记位置进行排列组合,完成 IMU 布局优化实验流程设计,并搭建能够实现数据采集与角度曲线显示同步进行的 IMU 测量系统。最后基于上述方案进行 IMU 布局优化实验,对 IMU 采集的数据进行分析。针对实验中作为参考标准的光学动捕系统的使用流程,选择符合本实验要求的反光标记点贴放方式,并将光学系统采集的数据导入 Visual 3D 建立下肢骨骼模型,输出精确的膝关节角度数据。通过对比 6 个布局的均方根误差,确定了大腿前下部和小腿外侧中部是贴腹弯腿动作下 IMU 组合的相对最优布置位置,平均均方根误差为 0.6°±0.26°,同时验证了提出的基于 IMU 组合布局的膝关节角度测量方法的有效性和准确性。最后,基于膝关节角度测量方法进行应用评价。利用得到的 IMU 最优布局方案,记录了膝关节从水平位置屈曲到极限位置整个过程中的关节角,其平均误差达到 1.23°,验证了该方法在关节活动范围(Range of motion,ROM)评价方面的可行性。同样利用该方法对比了膝关节与机器人关节角度在康复运动过程中的变化趋势,验证了该方案进行人机耦合性能评价的可行性。

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(a) 基于光学动作捕捉系统的 IMU 布局优化实验场景图

(b) 反光标记点在实验对象右腿上贴放位置示意图

图 4-2 Nokov 光学动捕实验图

NOKOV 度量动作捕捉在研究中的应用摘录

本文选用 Nokov 光学动作捕捉系统作为参考标准，来确定 IMU 测量系统的测量精度。该动捕系统通过红外镜头捕捉反光标记点，并构建三维模型进行数据分析[79]。本文搭建的动捕测量系统主要由 8 个动作捕捉镜头、云台等装置及 seeker 软件组成，可以全方位监测膝关节运动，实时性好，捕捉精度高。

引用格式 陈海蝶. 基于 IMU 的膝关节转角测量及在康复训练中的应用研究[D].哈尔滨工业大学,2022.DOI:10.27061/d.cnki.ghgdu.2022.002199.

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基于 YOLOv8-pose 的施工人员疲劳姿势监测和调整系统研究

关键词

疲劳监测；施工人员；深度学习；计算机视觉；作业姿势评价

摘要

量化施工人员疲劳程度对减少施工不安全行为、保护工人生理性健康和提高现场的安全管理水平具有重要意义。基于 OWAS 和 RULA 姿态评估方法建立疲劳评价指标，并依托 NOKOV 动作捕捉系统和 YOLOv8-pose 算法检测分析施工人员的疲劳等级，建立了施工人员疲劳作业姿势评估和方案调整系统。通过试验验证了所提系统的有效性和可行性，结果表明：所提方法能够准确反映现场施工人员的疲劳程度，所提系统能够实现施工人员疲劳程度的自动化检测并提供对应的调整方案。

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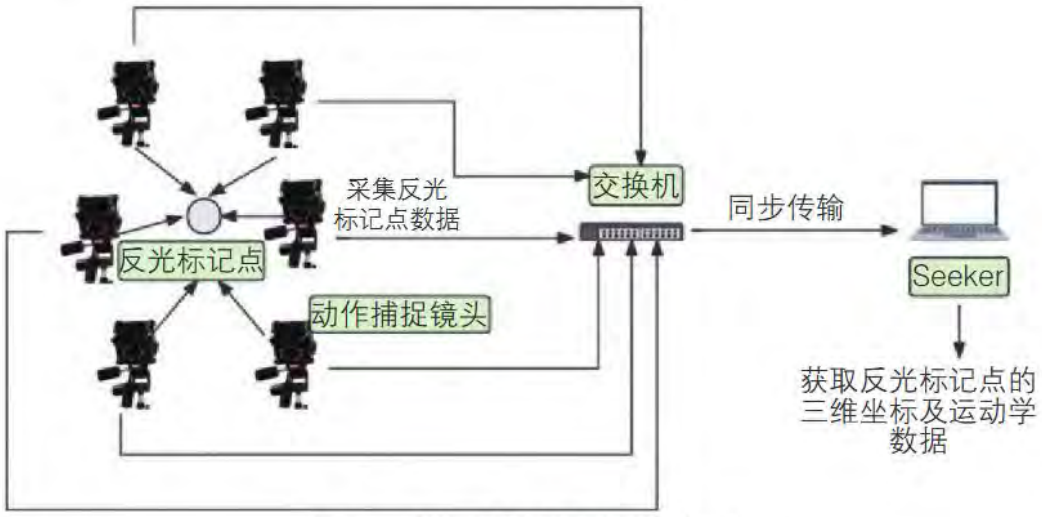

图4　动作捕捉数据采集方案

NOKOV 度量动作捕捉在研究中的应用摘录

NOKOV 动作捕捉分析系统基于被动式光学原理，利用多目立体视觉测量技术，结合计算机图像处理技术和先进算法，将标记点位置和动作转化为数据信息。本研究借助 NOKOV 光学动作捕捉系统对人体关键骨骼节点进行重构。其中包括 6 个 NOKOV 动作捕捉系统镜头、1 台交换机和 1 台上位机。动作捕捉镜头布局呈矩形分布，覆盖区域大小为 4.2 m×3.6 m，镜头安装高度为 2.2 m。数据处理工作通过 Seeker 软件完成。具体方案如图 4 所示。

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基于动作捕捉的帕金森运动迟缓量化评估技术研究

关键词

帕金森病；运动迟缓；动作捕捉；量化评估；支持向量机；深度学习

摘要

帕金森病(Parkinson's disease,PD)是一种常见于老年人的神经系统退化性疾病,通常伴随着不同程度的运动和非运动性症状。运动迟缓是帕金森病的主要临床表现之一,也是作为临床筛查和诊断的一个主要依据。目前,帕金森病的诊断监测主要依赖于医生的个人感觉和临床经验,具有不同程度的主观性和个体差异性。因此,对 PD 患者的运动症状进行量化评估是 PD 诊疗中的一个难点和重点。

本文基于光学三维动作捕捉设备,通过对帕金森患者上肢和下肢精细动作的捕捉,深入分析帕金森病人的运动迟缓症状。针对动作捕捉系统的高精度特性,对记录得到的原始信号进行去噪、预处理、以及相关特征的提取等操作,并且建立帕金森运动迟缓症状的量化评估技术。本文的主要内容概括如下:

(1)基于高精度光学动作设备的量化检测系统的设计与搭建,并且针对帕金森患者设计了相应的实验范式,建立运动迟缓数据库,用于进一步量化评估。

(2)深入研究了帕金森运动迟缓症状的生理和临床特性,基于帕金森病综合评分量表(the Unified Parkinson's Disease Rating Scale,UPDRS)所要求的准则对动作捕捉数据进行特征的手动提取,特征提取主要依据幅值、速度、平滑性三个方面,在健康人和不同严重程度的帕金森患者之间具有区分性。

(3)采用多种监督学习方法建立量化评估模型,用于帕金森患者与健康人之间的二分筛查和不同严重程度的帕金森患者之间的细化分级。并且针对实验数据中的类别不平衡问题,讨论 CS-SVM 模型相比于欠采样和过采样方法能有更好的效果,实验结果证明了手动特征提取的有效性和分类评估的准确性。

(4)更进一步地,通过深度学习,讨论数据扩增方法和端对端的 LSTM 与 GRU 网络方法对原始时序数据进行训练可以提高分类准确率,优化评估效果。最终的实验结果证明了本研究中的一系列数据处理、特征提取和学习方法面对实验对象的不同严重程度的运动迟缓动作具有区分性,验证了光学动作捕捉设备用于帕金森量化评估的可行性和可靠性,具有较大的实用意义。

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图 2.1: Nokov 动作捕捉系统包含摄像头、三脚架、交换机和网线等主要硬件

图 2.2: 动作捕捉系统的反光标记点和场地标定所需的 L 型杆、T 型杆

NOKOV 度量动作捕捉在研究中的应用摘录

研究中采用 Nokov 公司的光学三维动作捕捉系统，设计方案用于实际中的医院临床环境，作为帕金森病运动症状的量化检测平台。整套系统分为硬件和软件两大部分，硬件包括信号发射与接收设备、 传输设备、空间定位标杆等， 软件包括动作捕捉界面显示、数据处理等功能模块。如图 2.1 和 2.2 所示，整套系统硬件平台主要包括具有亚毫米级捕捉精度的红外光学摄像头、小巧无源的反光标记点(Marker)、交换机以及 L 型、T 型标定杆以及网线等其他若干组件。

Nokov 光学动作捕捉系统采用被动式红外光学原理设计，摄像头之间采用并联方式连接，在保证高实时性的同时提高了系统的稳定性；采用集成 POE 数电同传技术——从镜头至连接器能保证数据的实时迅速传输，使捕捉目标的每一个动作都能反映在三维工作界面中。通过在人体运动的关键部位粘贴反光标志点，可以对相机发出的红外光线进行反射，由三维动作捕捉系统捕捉标志点位置，当人体运动时，系统可以实时地进行数据采集并以三维动画的形式进行

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基于反优化的人体下蹲动作预测仿真研究

关键词

反优化；预测仿真；直接配点法；PSO 算法；OpenSim

摘要

分析人体中枢神经系统运动控制机制,在仿真环境中预测人体运动控制行为,是神经力学领域的重要课题,对穿戴设备设计优化、人机协作研究具有重要意义。但人的控制机制至今尚不明朗,难以通过机理手段建模。本文根据人体运动控制中展现出的优化原则,借助 Open Sim 开源平台,开展下蹲动作预测仿真研究。人体运动一般为多目标优化,建立合理的目标函数是搭建预测仿真框架的主要挑战。现有研究多以手动调整的形式给出目标函数权重,缺乏科学性。本文基于反优化思想,通过构建双层优化框架,求取目标函数权重,从而实现下蹲动作预测仿真。主要研究工作如下:(1)基于优化原则搭建人体下蹲动作预测仿真模型。基于人体运动行为中表现出的优化原则,根据人体肌肉骨骼动力学模型构建下蹲动作的预测仿真框架。基于反优化思想,构建双层优化框架,求解目标函数。分析上下层优化问题特性,分别以粒子群(Particle Swarm Optimization,PSO)算法和直接配点法为上下层优化求解算法,完成对动作预测框架的整体搭建。(2)针对上层优化中标准 PSO 算法的缺陷进行改进。首先,提出一种参数自适应调整法则,对影响粒子搜索性能的三个主要参数,即惯性权重、社会和自我认知加速度系数,进行改进。其次,基于提出的参数自适应调整法则,对改进 PSO 算法的收敛性进行理论分析与证明,得到算法收敛的参数收敛条件,给出保证算法充分收敛的参数设置法则。最后对改进有效性进行验证。(3)人体下蹲动作实验设计和预测仿真平台搭建。使用运动捕捉系统和测力平台采集下蹲动作的运动学和动力学信息,并利用 Open Sim 工具解算下蹲动作运动学与动力学信息。参考现有人体模型,创建简化的单边肌肉骨骼模型,作为动力学约束。在 MATLAB 环境下搭建双层优化框架,实现目标函数的反优化求解与下蹲动作的预测仿真。实验结果表明:本文所建立的预测仿真可复现人体自主下蹲动作；改进的 PSO 算法性能较标准 PSO 算法平均提升了 22.28%。本文提出的基于反优化的运动预测仿真框架在实际应用上具有可行性和有效性,可为实现人体其他复杂运动的预测仿真提供一定的理论基础和实践参考。

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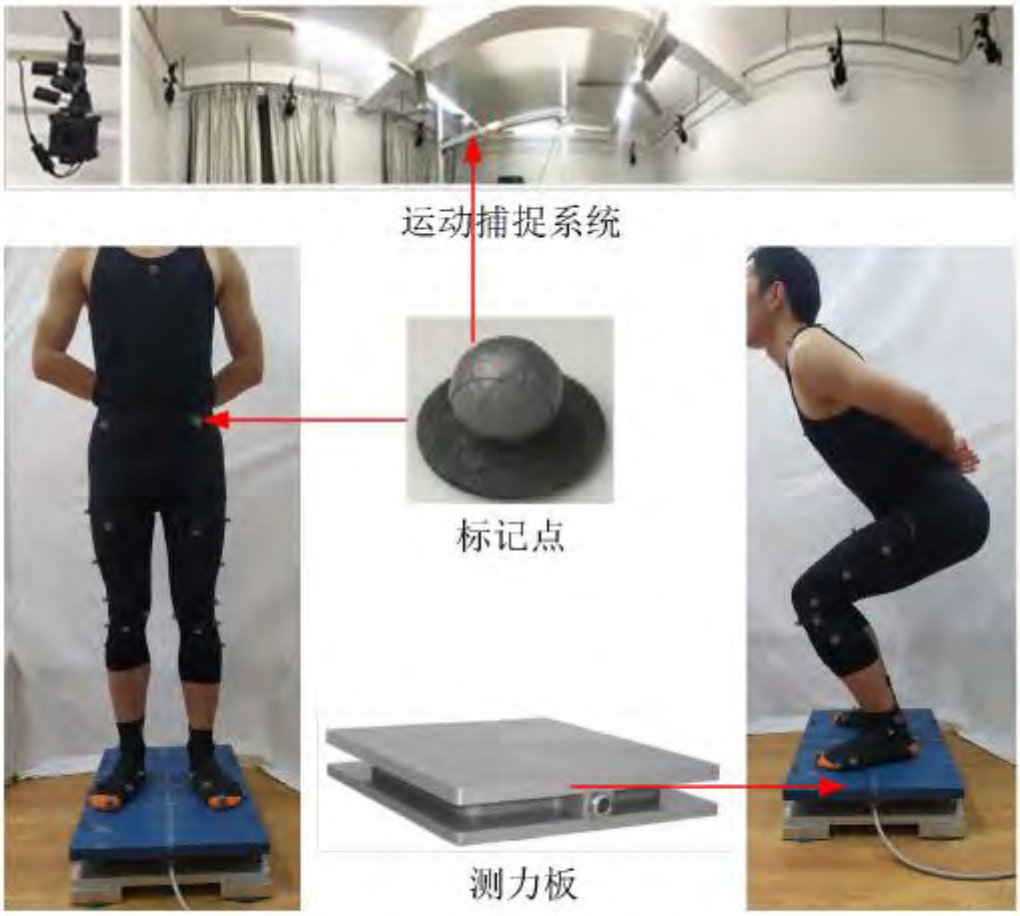

图 4-1 人体下蹲实验图

NOKOV 度量动作捕捉在研究中的应用摘录

使用运动捕捉系统和测力平台采集下蹲动作的运动学和动力学信息，并利用 OpenSim 工具解算下蹲动作运动学与动力学信息。参考现有人体模型，创建简化的单边肌肉骨骼模型，作为动力学约束。在 MATLAB 环境下搭建双层优化框架，实现 H 标函数的反优化求解与下蹲动作的预测仿真。

引用格式 肖婷.基于反优化的人体下蹲动作预测仿真研究[D].武汉理工大学，2021.DOI：10.27381/d.cnki.gwlgu.2021.000421.

链接
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基于光学传感器的滑雪动作捕捉系统研究

关键词

光学传感器；运动捕捉；Unity3D

摘要

滑雪是一种高速运动项目，对运动员的技术要求很高。基于光学传感器的滑雪运动捕捉系统能够实 时监测运动员的动作，并提供实时反馈，以帮助运动员改进其技术。本研究采用光学传感器来捕捉运动员 的运动轨迹和姿势，通过 Unity3D 平台实时分析和评估运动员的动作。实验结果表明，该系统能够准确捕 捉运动员的动作，并且能够提供准确的运动数据，对提高运动员训练和比赛表现具有积极的意义。

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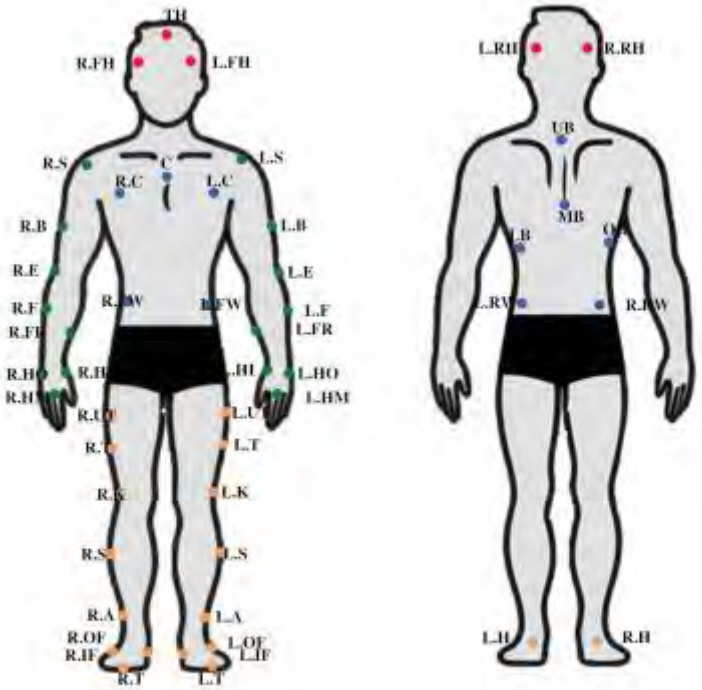

图 2　反光小球人体分布图

NOKOV 度量动作捕捉在研究中的应用摘录

本系统主要采用 Nokov 光学动作捕捉镜头，捕捉室内模拟滑雪场下运动的姿态，传输方式是以 RJ45 的有线方式，最后上位机是采用 Unity3D 来进行动画模拟。首先将反光材质的 Marker 点贴在人体的主要关节点，光学动作捕捉系统依靠反光小球作为标记点，通过采集被测物体标定位置在三维空间中的运动轨迹，并实现人体运动重建 4;上位机部分采用建模软件建立人体模型，将建立的人体模型导入 Unity3D 中，在 Unity3D 中可以接收数据并且驱动人体模型运动，从而使人体运动姿态可视化。滑雪运动捕捉系统如图 1 所示。

引用格式 信广旭,韩成浩.基于光学传感器的滑雪动作捕捉系统研究[J].电器工业,2024,(12):44-48.

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https://kns.cnki.net/kcms2/article/abstract?v=6h6U53PWxNQhaLJcnY5jDWZyBlI55GtNG2_5QERLA4kkKXcHskzOuvWuvJjrO_JAovuSrRKD8ZFZGnCYpcJMoDBEbWqlMaRX6SNmsYpBMI0L3vPJeTNYhj8NwSizSdXzJvwqPWdIrV8KGsCFrT3T_ybHPjH0rb09G0KEE5V6avG4-j0vRrabEuXVcmxe3mAF&uniplatform=NZKP

基于混合动作捕捉技术的体育辅助训练系统

关键词

体育辅助训练系统；动作捕捉；人机交互；运动评价；乒乓球

摘要

随着我国体育锻炼人数的逐年增加，体育教练资源短缺的问题愈加明显。尤其是在中西部地区，基础体育教学尚未完全普及。动作捕捉作为一种数字化记录运动物体位置和姿态的手段，为体育运动的数字化提供了技术基础。基于动作捕捉技术的数字化体育训练有望减少训练过程中对教练员的经验依赖，实现更加普遍的体育基础教育。本文研究了适用于绝大多数运动项目的体育辅助训练问题，主要创新点如下:本文首先在归纳传统体育训练模式的基础上，提出了基于知识的通用体育辅助训练框架。框架包含领域知识、受训者、运动评价和控制器四个主要模块。领域知识模块是对该项运动的练习内容、改进指令、技能指标等知识的数字化表示；受训者模块是受训者对练习内容和改进指令的动作反应；运动评价模块使用动作捕捉技术获得受训者的原始运动数据，并进一步计算得到运动特征；控制器模块依据运动评价的结果，对受训者提出改进指令或使其练习新的内容，直到受训者达到预期目标。之后，研究了通用体育训练框架在具体运动中的实施方法，即，领域知识的表达和动作捕捉系统的搭建。本文乒乓球为例，描述了框架中练习内容、运动特征和技能水平的具体形式，明确了适合于乒乓球的动作捕捉方式及运动特征的计算方法。同时，为进一步提高惯性动作捕捉系统对受训者位姿的还原精度，本文从双脚接触判断和基于接触位置约束的位姿修正两方面对原有的惯性动作捕捉系统进行了改进。仿真结果显示，修正后的人体位姿具有良好的动作平滑性。最后，开展了通用框架在乒乓球领域的应用示范。本文搭建了基于混合动作捕捉技术的乒乓球辅助训练系统，并邀请不同水平的乒乓球爱好者参与实验。实验表明:针对同一套练习内容下的不同受训者，系统计算得到的受训者水平（回球质量和动作标准性）与实际情况一致。实验结果初步验证了搭建系统的有效性，为今后进一步研究高精度、交互式的体育辅助训练系统奠定了基础。

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表 4-3 实验器材选用表

设备	品牌型号	实验需求	额外处理
发球机	OUKEI	可调整上下旋发球，定点发球	定期调整或更换旋转滚轮松紧度
光学动捕	Nokov	高帧率以捕获轨迹关键点，稳定性好，不会混淆反光球	定期扫场，使用前清理场地，自编程序实现快速后处理
惯性动捕	Legacy	以较高帧率输出人体主要骨骼的姿态和位置，传感器续航足够	由压力鞋垫提供更准确的接触判断，进而修正相关骨骼位姿
乒乓球	红双喜	与训练用球一致	在球的表面均匀覆盖反光材料
球拍	红双喜	不影响受试者发挥	在球拍护边及拍柄粘贴反光点

NOKOV 度量动作捕捉在研究中的应用摘录

根据实验需求，我们选择了相应的自动发球机、惯性动作捕捉系统、光学动作捕捉系统，并对乒乓球和球拍的反光性处理进行了说明，列于表 4-3。实验效果如图 4-2，文内提到的光学动作捕捉镜头、全身惯性动作捕捉套装、发球机、反光球、反光球拍等在图内均有标注。覆盖反光材料后的乒乓球相比普通球的重量偏大，相应的弹性、惯性等其他指标会有轻微变化。但在短时间的适应后，受训者一般能够习惯球的变化。

引用格式 闫伟超.基于混合动作捕捉技术的体育辅助训练系统[D].哈尔滨工业大学，2020.DOI：10.27061/d.cnki.ghgdu.2020.001575.

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https://kns.cnki.net/kcms2/article/abstract?v=3uoqlhG8C475KOm_zrgu4lQARvep2SAkyRJRH-nhEQBuKg4okgcHYgP6raK5npOEVcUuzC7G5HSa1TA3OPuCIUZMB0NgRgkW&uniplatform=NZKPT

基于人工神经网络的蹦床运动员竞技能力结构评价 模型的构建与应用

关键词

蹦床；竞技能力结构；人工神经网络

摘要

目的：建立蹦床运动员竞技能力结构评价指标体系，在此基础上构建基于人工神经网络的蹦床运动员竞技能力结构评价模型，为蹦床运动员竞技能力结构的个性化诊断及针对性训练提供参考。方法:以上海市体操运动中心 16 名蹦床运动员为研究对象，对受试者进行 3 次跨度 6 个月以上的初选指标测试。基于因子分析建立蹦床运动员竞技能力结构评价指标体系。在此基础上以竞技能力结构评价指标为自变量，运动员成绩为因变量，构建运动员竞技能力结构的人工神经网络评价模型，并开发运动员竞技能力结构评价系统。结果：蹦床运动员竞技能力结构指标体系由身体形态、身体素质、专项技术和心理素质 4 个维度构成，包括腿长、腿长/身高比、纵跳高度、原地立臂角度、60s 悬垂举腿、立卧撑、网上腾空高度、空跳高度/原地纵跳高度比、着网瞬间立臂角度、30 次空跳高度下降率、状态焦虑水平和特质焦虑水平共 12 个指标。所构建的 Elma 人工神经网络模型由 12 个输入节点、9 个隐含层节点和 1 个输出层节点组成，模型预测精度在 95.87%\~99.37%，平均预测精度高达 97.66%。结论：构建了基于人工神经网络的蹦床运动员竞技能力结构评价模型，模型具有较好的预测精度。在训练中，可应用人工神经网络对竞技能力结构进行评价，动态获知竞技能力结构改变对总体运动成绩的影响作用。该研究对于蹦床运动员竞技能力结构的综合评价和针对性训练可提供科学性指导意见。

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NOKOV 度量动作捕捉在研究中的应用摘录

在蹦床网上进行专项技术指标的测试。 受试者分别进行 30 次最大能力的连续空跳、一周半空翻和两周半空翻，共 3 次测试。采用 8 台 Mars2 型号红外高速摄像头的三维运动捕捉系统（ Nokov 科技公司生产）对受试者测试过程中的运动学参数进行采集， 获取网上腾空高度、 触网时间、30 次空跳高度损失率、一周半空翻速度、两周半空翻速度、入网瞬间立臂角度、入网角度、压网深度/体重、水平位移等专项技术指标。其中，一周半空翻速度和两周半空翻速度为所翻转的角度（ 分别为 540°和 900°）除以空翻所用时间，单位为（°）/s。

引用格式 王乐军,王钰婷,龚铭新等.基于人工神经网络的蹦床运动员竞技能力结构评价模型的构建与应用[J].体育科研,2022,43(05):84-90.

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基于人体运动建模的逆运动学算法研究

关键词

运动建模；逆运动学；循环坐标下降；BFGS

摘要

为提高逆运动建模的速度，并针对传统逆运动学数值法精度不高的问题，提出了一种循环坐标下降算法和 BFGS 算法结合的逆运动学求解算法。首先利用三维动作捕捉系统得到人体的运动数据，并建立人体的关节模型；然后对循环坐标下降和 BFGS 结合的算法的实现方法进行分析；最后通过仿真实验验证了算法的可行性。

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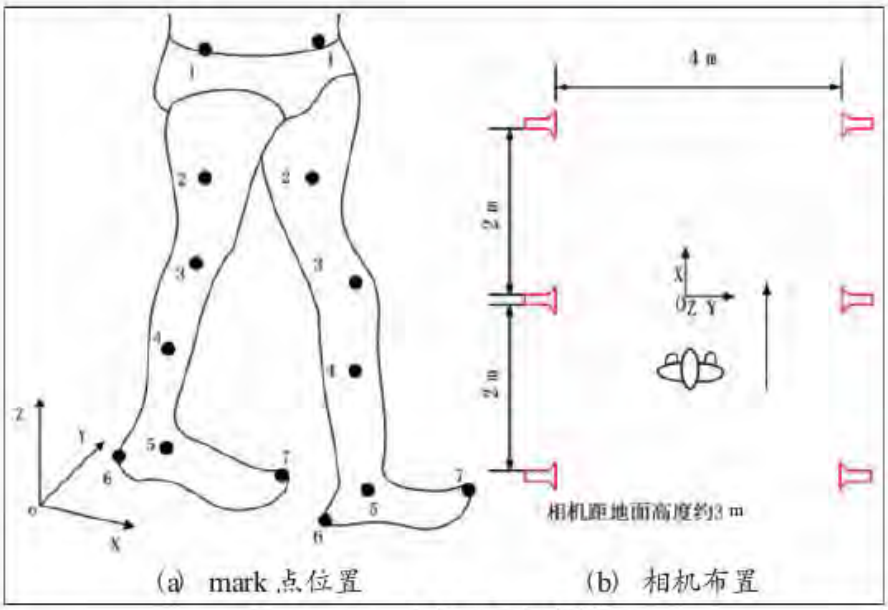

图 1　mark 点位置和相机布置

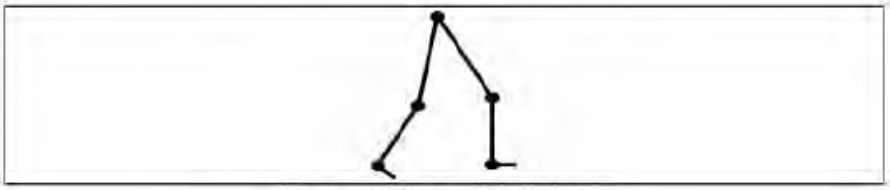

图 2　人体下肢关节模型

NOKOV 度量动作捕捉在研究中的应用摘录

本文用 NOKOV 三维红外被动式光学运动捕捉系统来实时捕捉人体的下肢运动数据。所用动作捕捉系统主要由 6 个相机、上位机、mark 点、定位杆、校正杆等组成。每个 mark 点只要同时被 2 个镜头捕捉到，便能记录下 mark 点的坐标，进而得到特定点随时间变化的连续运动轨迹。运动捕捉系统以每秒 100 帧的速率记录所有标记点的空间坐标，并且其捕捉精度可达 1mm。动作捕捉系统中 mark 点位置和相机的布置如图 1 所示。

人体下肢是一个极其复杂的系统，为了便于研究，一般将下肢分为髋关节、膝关节、踝关节、大腿和小腿 5 部分。这样就可以把关节看作为点，大腿和小腿为链，如图 2 所示。每个关节都固定 1 个局部坐标系，根据欧拉角的表示方法，从子关节局部坐标系旋转变换到父关节局部坐标系的旋转矩阵可以表示为公式（1）。

引用格式　蔡飞,胡宁宁,卢俊兰.基于人体运动建模的逆运动学算法研究[J].企业科技与发展,2019(03):76-78.

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基于任务导向训练的上肢多模态特征融合评估方法研究

关键词

脑卒中;运动功能评估;肌肉协同;多模态特征融合;功能评分机制;

摘要

随着人口老龄化现象日益突出,由脑卒中导致的运动功能障碍患者比例逐步增加。脑卒中患者常常伴随上肢运动功能障碍,对日常生活能力和生活质量造成了严重影响。依据大脑神经可塑性原理,特定的运动功能训练有助于患者实现肢体康复。然而,现有的上肢康复训练方案在个性化设计和实际效果上仍有不足。因此,对脑卒中患者进行康复训练后的上肢运动功能评估显得尤为重要。临床上主要通过临床量表进行功能评分,这种评估结果严重依赖临床经验,缺乏客观性。为更好地对患者上肢功能状态进行定量评估,本研究从协同效应量化模型构建、多模态特征融合评估模型框架制定以及上肢运动功能评估系统设计三方面展开。 主要研究内容如下: (1)针对运动缺陷导致的异常病理性协同分析问题,构建协同效应量化模型,给出评估运动功能的可靠性指标。通过分析人体上肢骨骼和肌肉结构,结合关节活动度特性,设计充分映射上肢功能状态的任务导向库。利用奇异值分解和 K 加权角相似度算法搭建量化模型,对相同任务导向下患者组与健康对照组的运动协同和肌肉协同效应进行对比实验,实验验证患者组与健康对照组在协同效应分析中的差异,为实现基于多模态特征融合的上肢运动功能评估奠定基础。 (2)针对上肢运动功能全面定量评估问题,提出上肢多模态特征融合评估框架,定量评估受试者上肢运动功能状态。通过机器学习算法依次构建局部分类器和集成分类器,将输出结果整合提出多模态特征融合评估模型,对受试者正常或病理性运动模式进行定性分类,并依据三种分类模型分别预测受试者运动模式属于病理性模式的概率设计能反映上肢运动损伤程度的新型功能评分机制。实验表明新型上肢运动功能评分机制在用于定量评估临床患者的上肢运动功能障碍程度具有应用价值。 (3)针对上肢运动功能实现智能化评估问题,设计一种高效的上肢运动功能自动化评估系统,提高临床应用的实用性。基于 Matlab 和 Pycharm 软件,从原始数据读取模块、预处理模块、特征提取与协同效应量化模块、数据集更新模块、数据集可视化模块和模型评估模块设计自动化评估系统。通过采集患者组与健康对照组在相同任务导向下的运动数据和表面肌电信号进行实验,实验表明自动化评估系统能够对患者康复训练后给出定量康复效果评价,为更好的实现临床应用奠定基础。

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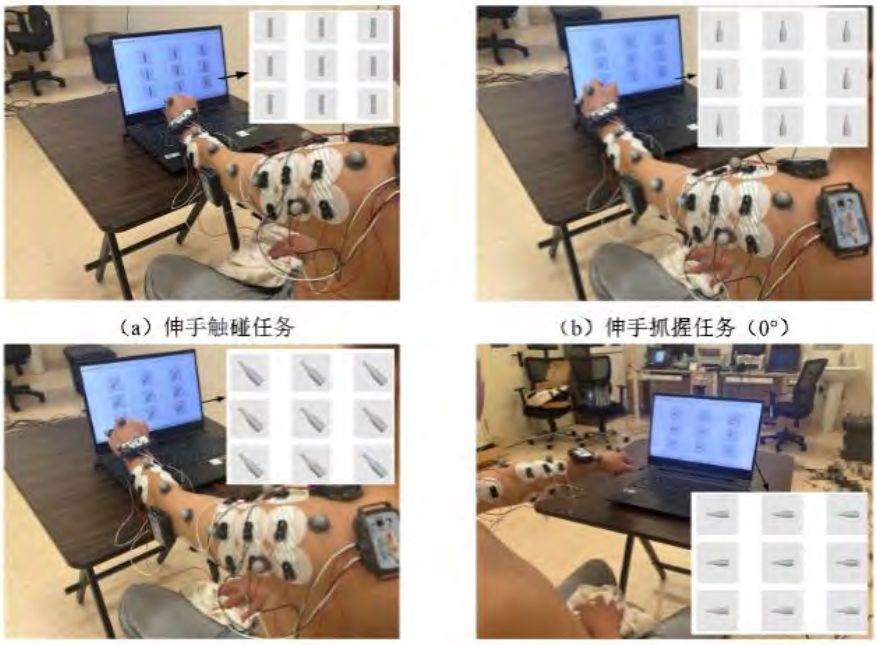

（a）伸手触碰任务　（b）伸手抓握任务（0°）

（c）伸手抓握任务（45°）　（d）伸手抓握任务（90°）

图 3-1 目标导向任务示意图

NOKOV 度量动作捕捉在研究中的应用摘录

本文采用 NOKOV 度量光学三维动作捕捉系统,主要由动作捕捉镜头、动作捕捉软件和动作捕捉附件三个部分构成。其中，动作捕捉附件包含镜头固定装置、镜头连接线(包括网线和 POE 分离器)、交换机、标定杆(L 型与 T 型)以及 Marker 点。动作捕捉镜头为 Mars 系列，如图 2-3 所示。其型号 Mars12H 分辨率可达 1200 万像素。NOKOV 光学三维动作捕捉系统通过排布在空间中的动作捕捉镜头，对室内空间的捕捉区域进行覆盖，并对捕捉目标上放置的 Marker 点进行三维空间位置的精确捕捉，通过先进算法进行处理和运算，系统可得到不同时间计量单位上各个 Marker 点的三维空间坐标。同时也可对目标物进行刚体设置，通过专业分析软件对数据进一步处理和运算，可得到目标物体精确位置及姿态等三维数据。其中，三维人体模型结合运动学模型实时追踪肢体动作，动作捕捉镜头捕捉坐标信息，精度可达到亚毫米级动态性能优异，确保高效动作捕捉。

引用格式 刘广.基于任务导向训练的上肢多模态特征融合评估方法研究[D].长春工业大学,2025.DOI:10.27805/d.cnki.gccgy.2025.000580.

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基于运动轨迹图形拟合的辅助人体侧翻机构设计研究

关键词

侧翻；运动捕捉；运动轨迹；图形拟合；机构构型

摘要

仰卧位侧翻是长期卧床患者有效预防压力性损伤病症的有效措施之一，研究人体运动机理并进行辅助人体仰卧位侧翻机构的拟人化设计具有重要意义。人体肩部和臀部是辅助仰卧位侧翻较为关键的施力位置，基于人体解剖学分析肩部和臀部骨骼的空间运动，建立运动标记模型，并进行人体仰卧位侧翻运动捕捉实验，得到肩部和臀部的运动轨迹图形与连杆模型特征信息。通过分析连杆长度和角度的变化过程进行图形几何分析与连杆机构简化，基于运动轨迹图形拟合的辅助人体侧翻机构构型，并对机构进行运动学仿真分析，运动仿真结果和实验图形的拟合误差较小，验证了所提出的辅助人体侧翻机构拟人化设计方法的合理性，相关研究结果可为人-机运动协同性辅助侧翻康复辅具的设计提供理论依据。

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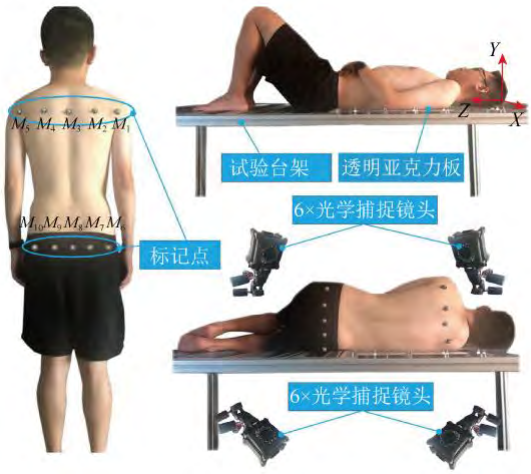

NOKOV 度量动作捕捉在研究中的应用摘录

使用度量科技公司的 NOKOV 光学三维动作捕捉系统，实验地点为北京信息科技大学。实验者均为男性志愿者，年龄 20\~24 岁，身高 170\~175cm，体重 55\~80kg，符合实验要求。搭建侧翻运动专用测试实验台，如图 3 所示，实验台床面由透明亚克力板搭成，在实验台的上方和下方均布置有 6 个光学捕捉镜头，在仰卧位侧翻初始姿态时，下方的光学镜头透过透明的亚克力板能够识别到人体背部的标记点。实验者肩部和臀部根据上述标记点建模情况各粘贴 5 个标记点，在仰卧位侧翻过程中，上方的光学镜头能够识别到侧翻姿态人体背部的标记点，实验者以双腿屈膝、双手置于腹部的姿势平躺于实验台上。

引用格式 苏鹏,卢达,伦庆龙等.基于运动轨迹图形拟合的辅助人体侧翻机构设计研究[J].图学学报,2020,41(06):993-1000.

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加减行气破瘀汤联合常规康复治疗对脑卒中后患者步态参数及肢体运动功能的影响

关键词

脑卒中;行气破瘀汤;康复治疗;步态;运动功能;

摘要

目的 观察加减行气破瘀汤联合常规康复治疗对脑卒中后患者步态参数及肢体运动功能的影响。方法 回顾性选取 2022 年 1 月至 2023 年 10 月焦作市中医院收治的 66 例脑卒中后患者为研究对象，按不同治疗方案分为康复组、联合组，各 33 例。康复组给予常规康复治疗，联合组在此基础上给予加减行气破瘀汤治疗。比较两组中医证候积分、临床疗效、步频、步速、步幅、步态周期时间、上肢肱静脉与下肢股总静脉的血流量(BF)/最大血流速度(PSV)、Fugl-Meyer 运动功能评分量表(FMA)、Tinetti 平衡与步态量表(TGBS)、Barthel 指数(BI)评分、不良反应。结果 治疗 1 个月后联合组半身不遂、神疲乏力、感觉减退、口舌歪斜积分均低于康复组(P<0.05)；联合组临床疗效 96.97%高于康复组 81.82%(P<0.05)；治疗 1 个月后联合组肱静脉、股总静脉的 BF、PSV 均高于康复组(P<0.05)；治疗 1 个月后联合组步速、步幅、步频均升高且高于康复组，步态周期时间缩短且短于康复组(P<0.05)；治疗 1 个月后联合组 FMA-上肢/下肢、TGBS、BI 评分较康复组更高(P<0.05)；两组不良反应发生率比较差异无统计学意义(P>0.05)。结论 加减行气破瘀汤联合常规康复治疗能改善脑卒中后患者肢体运动功能及步态稳定性，缓解临床症状，增强平衡能力，有利于提升生活质量。

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NOKOV 度量动作捕捉在研究中的应用摘录

1.4.4 步态参数比较两组治疗前、治疗 1 个月后 步 态 参 数，采 用 北 京 度 量 科 技 有 限 公 司 的 NOKOV 度量光学三维步态分析系统测定上述指标，嘱患者于机器上行走，记录步频、步速、步幅、步态周期时间。

引用格式 赵国顺,许静怡,张亚辉.加减行气破瘀汤联合常规康复治疗对脑卒中后患者步态参数及肢体运动功能的影响[J].中国疗养医学,2026,35(01):86-90.DOI:10.13517/j.cnki.ccm.2026.01.019.

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https://kns.cnki.net/kcms2/article/abstract?v=yqBhao7Q9gxXevskWHjutAmGkQ419kj4hH0OcapQQgK5J20wUBER9LJQxEhOaXopiv69pqBARjFAvjo0tsbwiYjXoxIBAOOzr35FJp-qrfdXhL5GZkRRL7XkOk6NSuwMjruDq1WEsMjzZUW7RXyRYIZdRNNYGRIWuw0jBTqsKoKxIkXL6ICMAA==&uniplatform=NZKPT&langua

静水划艇途中划专项技术特征及部分训练手段的专项性研究

关键词

静水划艇；专项技术特征；表面肌电；运动学

摘要

研究目的:通过对优秀静水划艇运动员的水上专项、测功仪和陆上模拟拉桨技术环节的运动学和表面肌电数据采集,分析水上拉桨和回桨的专项技术特征,并以此为根据评价拉测功仪和陆上划桨作为专项技术训练手段的合理性,为皮划艇运动员的训练实践提供理论参考。研究方法:使用Kine AI 无标记动作捕捉系统和 Delsys Tringo 肌电测试系统同步采集优秀划艇二级及以上十名运动员水上专项和陆上部分训练手段的运动学和表面肌电数据。运动学数据通过 Kine AI 无标记动作捕捉系统解析获得关节角度,该系统由 2 台采样频率为 60HZ 的 RGB 摄像机、无标记系统标定板和终端采集与分析软件组成。肌电数据通过 Delsys Tringo(16 导)测试系统采集后经移除平均值去漂移,带通滤波去噪,全波整流,低通滤波获得包络线。通过调用 Delsys 公司硬件产品提供的动态链接库(dll)开发的插件实现视频和肌电同步。拉桨和回桨为一个完整的周期,以撑桨手肩关节角度最大为零时刻,肘关节最小为拉桨结束时刻,后面是回桨阶段。 研究结果: (1)水上专项拉回桨的平均周期是 1.22 秒。拉桨时间均值为 0.78 秒,占比 59.2%;回桨时间均值为 0.5 秒,占比 40.8%。撑桨手:肘关节的起始角度为 176.6 度,拉桨结束角度为 18.8 度,幅度变化为 76.9 度至 96.7 度;肩关节开始角度为 171.6 度,结束角度为 37.4 度,幅度变化在 64.9 度至 99.3 度之间。拉桨手:肘关节的起始角度为 174 度,拉桨结束角度为 44.5 度,幅度变化在 26.8 度至 112.3 度;肩关节的起始角度为 116.9 度,结束角度为 0.9 度,幅度变化在 20.4 度至 93.5 度;撑桨手同侧髋关节的起始角度为 177.5 度,结束角度为 1.1 度,幅度变化在 30 度至 139 度;拉桨手同侧髋关节的开始角度为 174.6 度,结束角度为 30.9 度,幅度在 56.3 度至 99 度之间。其中肱二头肌(拉同侧)、斜方肌(拉同侧)、三角肌前束(撑同侧)、肱桡肌(撑)、腹外斜肌(撑同侧)是水上拉回桨动作的主要用力肌群,它们的激活顺序是肱桡肌(撑)、肱二头肌(拉同侧)、三角肌前束(撑同侧)、斜方肌(拉同侧),最后是腹外斜肌(撑同侧)。 (2)测功仪拉回桨的平均周期是 1.18 秒。拉桨时间均值为 0.68 秒,占比 57.7%;回桨时间均值为 0.49 秒,占比 42.3%。撑桨手:肘关节的起始角度为 168.2 度,拉桨结束角度为 43.5 度,幅度变化在 61.6 度至 95.8;肩关节开始角度为 166.8 度,结束角度为 16.2 度,幅度变化在 63.2 度至 122.1 度之间。拉桨手:肘关节的起始角度为 174.6 度,结束角度为 34 度,幅度变化在 44.9 度至 140.6 度;肩关节的起始角度为 154.1 度,结束角度为 6.1 度,幅度变化在 47.3 度至 126 度;撑桨手同侧髋关节的起始角度为 162 度,结束角度为 2.3 度,幅度变化在 42.8 度至 132.5 度;拉桨手同侧髋关节的开始角度为 175.9 度,结束角度为 51.5 度,幅度在 59.4 度至 97.8 度之间。其中肱桡肌(撑)、竖脊肌(拉同侧)、斜方肌(拉同侧)、胫骨前肌(撑同侧)、三角肌前束(撑同侧)是测功仪拉回桨动作的主要用力肌群,它们的激

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活顺序是胫骨前肌(撑同侧)、斜方肌(拉同侧)、肱桡肌(撑)、三角肌前束(撑同侧)最后是竖脊肌(拉同侧)。 (3)陆上模拟拉回桨的平均周期是 1.19 秒。拉桨时间均值为 0.69 秒,占比 57.8%;回桨时间均值为 0.31 秒,占比 42.2%。撑桨手:肘关节的起始角度为 174 度,拉桨结束角度为 53.8 度,幅度变化在 57.8 度至 109.9 度;肩关节开始角度为 175.9 度,结束角度为 34.5 度,幅度变化在 62.6 度至 134.2 度之间。拉桨手:肘关节的起始角度为 171 度,拉桨结束角度为 53 度,幅度变化在 52.2 度至 103.6 度;肩关节的起始角度为 142.9 度,结束角度为 18.6 度,幅度变化在 45.3 度至 119.7 度;撑桨手同侧髋关节的起始角度为 166.3 度,结束角度为 43.9 度,幅度变化在 50.2 度至 104.2 度;拉桨手同侧髋关节的开始角度为 177.6 度,结束角度为 32.8 度,幅度变化在 67.7 度至 115.3 度之间。其中竖脊肌(拉同侧)、斜方肌(拉同侧)、腹外斜肌(拉同侧)、竖脊肌(撑同侧)、三角肌前束(撑同侧)是陆上模拟拉回桨动作的主要用力肌群,它们的激活顺序是为竖脊肌(撑同侧)、腹外斜肌(拉同侧)、斜方肌(拉同侧)、竖脊肌(拉同侧)最后是三角肌前束(撑同侧)。(4)从动作周期上来看,水上专项运动员拉回桨时间较长,测功仪和陆上模拟的周期稍短。但测功仪的特点是拉桨时间更短,而陆上模拟是回桨时间更短。从关节角度上来看,三种条件下各关节的起始角度和运动幅度接近,但陆上模拟各关节运动幅度更大,测功仪拉回桨各关节运动幅度更小,水上专项居中。从主要用力肌群来看斜方肌(拉同侧)、三角肌前束(撑同侧)、肱桡肌(撑)是三种条件下拉回桨的主要做功肌群,且陆上模拟动作的主要用力与测功仪更为接近,但专项对上肢抓水和带水动作肌群的练习有较大作用。 研究结论: (1)静水划艇途中划的专项技术特征体现为高效的划桨周期控制、精确的关节角度调整以及主要用力肌群的有序激活。这些特征共同作用,使得运动员能够在保持速度和节奏的同时,最大限度地提高划艇效率和性能。 (2)尽管测功仪和陆上模拟动作在动作周期、关节角度和主要用力肌群等方面与专项拉桨技术存在一定差异,但总体而言这两个练习手段的专项性较高,可作为辅助的技术训练手段。

NOKOV 度量动作捕捉在研究中的应用摘录

光学动作捕捉系统 NOKOV 度量光学动作捕捉，结合三维测力台、表面肌电仪、足底压力测量仪等设备，用于分析人体走路、爬梯时的步态分析参数等运动学数据。三维步态分析系统 NOKOV（度量）光学三维动作捕捉系统，可采集研究对象亚毫米级精准的位置信息、路径形状和运动行为数据，用于步态分析和人机工效学研究。

引用格式 徐玉梅.静水划艇途中划专项技术特征及部分训练手段的专项性研究[D].江西师范大学,2024.DOI:10.27178/d.cnki.gjxsu.2024.001495.
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考虑动态平衡的起立意图预测

关键词

起立运动；动态平衡；外推质心；意图预测；支持向量机；神经网络

摘要

准确判断起立意图是构建外骨骼辅助策略的核心，但由于人体运动存在较大随意性，通过质心位移或角度阈值的方式难以准确捕获相位变换时刻。基于黑箱模型的识别方法虽然可以提高识别准确率，但缺乏生物力学层面的机理解释，难以预料识别结果。本文根据人体起立运动遵循的动态平衡规律，借鉴一种考虑起立运动速度的质心轨迹非线性处理手段，即外推质心，将质心轨迹直角坐标平面变换到动态平衡基准平面，降低特征数据对人体运动速度的依赖程度，提高起立意图判断准确性。本文分别使用支持向量机和神经网络对所提方法进行验证，与传统数据处理手段进行对比。结果显示，模型预测准确率均有提升。支持向量机预测准确率由 73.3% ~ 74.1%提升到 79.9%，起立时刻与预测时刻的时间偏差从 96ms ~ 101ms 降低到 70ms。神经网络的预测准确率从 81.2%提升到 86.2%，时间偏差从 87ms 降低到 59ms。

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NOKOV 度量动作捕捉在研究中的应用摘录

NOKOV 光学三维运动捕捉系统以 50Hz 的频率获取志愿者起立过程中的各肢体轨迹，实验过程如图 8 所示。通过肌肉骨骼系统仿真软件 OpenSim 解算运动过程中的动力学信息。

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篮球鞋中底硬度对疲劳状态下运动员下肢生物力学特征的影响研究

关键词

篮球鞋;中底硬度;疲劳状态;人体下肢;生物力学特征;

摘要

以 20 位达到国家二级运动员水平的男性篮球运动员为研究对象，对研究对象穿着不同中底硬度篮球鞋在疲劳状态下运动的下肢生物力学特征进行试验分析。结果表明，研究对象在疲劳状态下穿着中底硬度为 40 HS 的篮球鞋时膝关节稳定性更好、胫骨前肌肌肉兴奋程度更低，其下肢稳定性更好。

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图 3　测试过程

NOKOV 度量动作捕捉在研究中的应用摘录

1.1.2 试验设备
本试验主要分析篮球鞋中底硬度对疲劳状态下运动员下肢生物力学特征的影响，主要为运动员下肢肌肉活动情况分析。因此，试验所需设备除包括基础的红外人体动作捕捉设备(NOKOV，北京度量科技有限公司)、三维测力台「FP4060-10，维拓启创(北京)信息技术有限公司】外，还包括人体下肢表面肌电分析系统(YW-Symc，北京智通华宇科技有限公司)。图 1 为本试验所需设备图。

引用格式 王玲.篮球鞋中底硬度对疲劳状态下运动员下肢生物力学特征的影响研究[J].中国皮革,2025,54(11):61-64.DOI:10.13536/j.cnki.issn1001-6813.2025-011-014.

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篮球运动鞋鞋帮高度对足踝运动学的影响研究

关键词

篮球鞋；慢性踝关节不稳定；足踝；生物力学特征

摘要

为分析篮球运动鞋鞋帮高度对慢性踝关节不稳定患者足踝处的影响，选择 20 名慢性踝关节不稳定男性篮球爱好者分别穿着高、低帮篮球鞋进行篮球运动中最常见的 45°侧切变向动作，在研究对象运动过程中使用红外动作捕捉系统等对其足踝处的生物力学特征参数进行搜集。结果表明：高帮篮球鞋能够明显改善慢性踝关节不稳定研究对象在 45°侧切变向时的最大踝内翻角、最大踝内翻速度等，可以明显提升研究对象足踝部分稳定性。

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NOKOV 度量动作捕捉在研究中的应用摘录

本研究所需试验设备主要包括红外运动捕捉系统（NOKOV，北京度量科技有限公司）。红外运动捕捉系统具备实时跟踪测量并记录三维空间内点的轨迹、刚体的运动姿态及人体的动作的功能，主要用于对研究对象开展 45°侧切时的足踝触地时内翻角、最大内翻角、踝内翻活动幅度等参数进行搜集。

引用格式 李利.篮球运动鞋鞋帮高度对足踝运动学的影响研究[J].中国皮革，2024,53（04）：86-89.DOI：10.13536/j.cnki.issn1001-6813.2024-004-018.

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老年脑小血管病患者数字化运动测评的临床研究

关键词

脑小血管病；运动障碍；数字化；起立-行走计时测试；跌倒风险

摘要

研究目的分析老年脑小血管病(cerebral small vessel disease,CSVD)患者数字化起立-行走计时测试(digital timed up and go,dTUG)表现。研究方法选择 2021 年 9 月 2022 年 3 月解放军总医院第七医学中心干部神经内科连续住院的 CSVD 患者 49 例,按照 Fazekas 评分分为重度 CSVD 组 13 例(Fazekas 评分 23 分),非重度 CSVD 组 36 例(Fazekas 评分 01 分)。同期另选择健康体检者 11 例为对照组。记录人口学特征、利用唐顿跌倒风险指数(Downton fall risk index,DFRI)评估被试跌倒风险、传统起立-行走计时测试(timed up and go,TUG)用时,利用 NOKOV 动作捕捉系统采集 dTUG 各项参数(包括时相 1 用时、时相 1 摆动幅度、时相 2 用时、时相 2 摆动幅度、时相 3 用时、时相 4 用时,时相 4 摆动幅度、时相 5 用时),分析比较各组 TUG 总用时、各时相用时、坐-起及直线行走阶段的摆动幅度。研究结果 3 组性别、年龄、MMSE 评分比较,差异无统计学意义(P>0.05)。3 组 DFRI 评分比较,差异有统计学意义(P<0.01)。重度 CSVD 组 DFRI 评分明显高于对照组和非重度 CSVD 组,差异有统计学意义(P<0.05)。与对照组及非重度 CSVD 组比较,重度 CSVD 组 DFRI 评分、时相 3 用时、时相 4 用时明显延长[3.00(3.00,6.00)分 vs 2.00(1.00,3.00)分、2.00(0.00,4.00)分,P<0.05；(2.81±1.53)s vs(1.95±0.91)s、(2.13±0.61)s,P<0.05；(2.88±1.01)s vs(2.05±0.95)s、(2.35±0.65)s,P<0.05],时相 3 角速度明显变慢[(1.19±0.42)°/s vs(1.73±0.44)°/s、(1.51±0.41)°/s,P<0.05]。研究结论老年 CSVD 患者行 dTUG 测试表明时相 3 转身中的用时延长和转身角速度变慢,时相 4 用时延长,提示日常活动中存在较高跌倒风险和潜在运动障碍。

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NOKOV 度量动作捕捉在研究中的应用摘录

应用NOKOV(度量)光学三维动作捕捉系统对受试者进行TUG试验数据采集。NOKOV三维动作捕捉系统是如今是一款使用现今最新技术光学式运动捕捉系统。在记录和分析身体活动，步态，功能和姿势变化方面有强大功能。本实验所应用的光学式运动捕捉系统有12个相机，环绕表演场地排列，这些相机的视野重叠区域就是受试者的动作范围。为了便于处理，受试者穿上单色的服装，在身体的关键部位，如肘、关节、骸部、腕等位置贴上一些特制的标记物或发光点，称为"Marker",视觉系统只处理和识别这些标志。

引用格式 周宏华. 老年脑小血管病患者数字化运动测评的临床研究[D].南方医科大学,2023.DOI:10.27003/d.cnki.gojyu.2023.000888.

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老年脑小血管病患者运动测评的临床研究

关键词

大脑小血管疾病；意外跌倒；步行；运动障碍

摘要

目的 分析老年脑小血管病(CSVD)患者仪器化起立-行走计时测试(iTUG)表现。方法 选择 2021 年 9 月至 2022 年 3 月解放军总医院第七医学中心干部神经内科连续住院的 CSVD 患者 49 例，按照 Fazekas 评分分为重度 CSVD 组 13 例(Fazekas 评分 2 ~ 3 分),非重度 CSVD 组 36 例(Fazekas 评分 0 ~ 1 分)。同期另选择健康体检者 11 例为对照组。记录人口学特征、利用唐顿跌倒风险指数(DFRI)评估被试跌倒风险、传统起立-行走计时测试用时，采集 iTUG 各项参数，包括时相 1 用时、时相 1 摆动幅度、时相 2 用时、时相 2 摆动幅度、时相 3 用时、时相 4 用时，时相 4 摆动幅度、时相 5 用时。结果 与对照组及非重度 CSVD 组比较，重度 CSVD 组 DFRI 评分、时相 3 用时、时相 4 用时明显延长\[3.00(3.00,6.00)分 vs 2.00(1.00,3.00)分、2.00(0.00,4.00)分；(2.8±1.5)s vs(2.0±0.9)s、(2.1±0.6)s；(2.9±1.0)s vs(2.1±1.0)s、(2.4±0.7)s,P<0.05],时相 3 角速度明显变慢\[(1.2±0.4)°/s vs(1.7±0.4)°/s、(1.5±0.4)°/s,P<0.05]。结论 老年 CSVD 患者行 iTUG 测试表明时相 3 转身中的用时延长和转身角速度变慢，时相 4 用时延长，提示日常活动中存在较高跌倒风险和潜在运动障碍。

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试验同传统 TUG 试验在程序上一样。即从椅子上站起(时相 1),以正常速度走 3 m(时相 2),转身(时相 3),3 m 行走返回(时相 4),转身坐下(时相 5)。 利用 NOKOV 动作捕捉系统,对 iTUG 总时间和各分相拆分时间进行分析,并统计直线行走过程中最大摆动幅度。

引用格式 周宏华,赵弘轶,宋志澄等.老年脑小血管病患者运动测评的临床研究[J].中华老年心脑血管病杂志,2022,24(12):1251-1253.

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垒球绕环式投球动作缺失数据修复方法研究

关键词

垒球绕环式投球动作；缺失数据；修复

摘要

当前数据修复方法依据垒球运动学关系，构建模型对垒球绕环式投球动作缺失数据进行修复，需要收集大量的骨骼信息先验知识。提出一种基于稀疏表示的垒球绕环式投球动作缺失数据修复方法，将动作捕获设备贴在垒球运动员关节和末端处，以一定的频率对动作数据进行采集，通过重构获取标记点在三维空间中的位置，以 ASF＆AMC 的数据格式对垒球绕环式投球动作数据进行存储，给出垒球绕环式投球动作数据捕获过程。针对某一含有缺失标记的垒球绕环式投球动作帧，求出该帧中未缺失部分在由完整帧构成的字典上的稀疏表示系数，通过该稀疏表示系数与字典对动作帧中的缺失数据进行修复。实验结果表明，所提方法具有很高的修复精度。

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图 2　实验现场图

Fig. 2　The experiment site map

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2 实验结果分析
2.1 实验数据选择
通过 NOKOV 动作捕获设备对某体育学院 5 个垒球运动员的绕环使投球动作进行捕获，共捕获 50 个动作序列，随机选择其中的 5 个序列作为测试数据。通过对上述测试数据进行实验，得到修复结果，从而验证本文提出的基于稀疏表示的垒球绕环式投球动作缺失数据修复方法的有效性，　实验现场图用图 2 进行描述。

引用格式　王琳,石琼.垒球绕环式投球动作缺失数据修复方法研究[J].科学技术与工程,2016,16(36):196-200.

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连续触点运动中障碍物影响个体运动的认知神经机制

关键词

运动计划；触点运动；背外侧前额叶；功能性近红外光谱脑成像技术（fNIRS）

摘要

为了探究连续触点运动中障碍物对个体运动轨迹的影响，采用运动捕捉系统及近红外光谱脑成像技术（fNIRS），监测并分析了 20 名普通大学生在有、无障碍物情境下完成连续触点运动时的运动轨迹及大脑皮层活动。结果发现：相比于无障碍物条件，当连续运动中有障碍物时，周围运动区间的平均运动高度更高；障碍物对后面区间内的运动高度的影响程度显著高于前面的区间。另外，个体在有障碍物条件下双侧背外侧前额叶及双侧布罗卡区岛盖部的激活强度显著低于无障碍物条件，且障碍物对个体平均运动高度的影响越大，右侧这两个区域的激活水平越低。这说明障碍物对其前后运动区间内的运动轨迹都产生了影响，支持了物体可供性及计划再利用的观点，背外侧前额叶及布罗卡区岛盖部可能参与了这一加工。

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1987

NOKOV 度量动作捕捉在研究中的应用摘录

运动捕捉仪。采用北京度量科技生产的 Nokov 光学三维运动捕捉系统（Mars4H, NoKovCorporation,Beijing,China），来追踪被试的运动轨迹。在木棍的顶端和中间分别固定好一个反光标示点，并使用 8 个高功率的 HLED 发光器来捕捉木棍（标示点）的运动轨迹及跨越障碍物的情况。该设备的采样率为 100Hz。

引用格式 白学军,张琪涵,赵光等.连续触点运动中障碍物影响个体运动的认知神经机制[J].心理与行为研究,2019,17(02):145-152.

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慢跑鞋跟掌落差对人体慢跑状态下肢关节负荷的影响研究

关键词

慢跑鞋； 跟掌落差； 下肢关节负荷； 竞技水平

摘要

以 10 位具有一定慢跑经验的男性长跑爱好者为研究对象， 以跟掌落差分别为 0、 5、 10、 15 mm 的慢跑鞋为测试用鞋，借助红外高速运动捕捉系统对研究对象开展慢跑时的下肢关节负荷进行获取， 借助 Cortex 软件对获取数据对比情况进行分析。结果表明，当跑鞋跟掌落差为 0 mm 时， 慢跑鞋对研究对象下肢 关节出现运动损伤的风险性最低；当跑鞋跟掌落差为 10 mm 时， 研究对象的慢跑水平最高。

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1989

(a) 红外高速运动捕捉系统

(b) 三维测力台

(c) 测速系统

图 2 测试设备

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本次研究测试项目主要包括研究对象在慢跑过程中下肢膝关节和踝关节等的负荷。这些指标主要通过矢状面关节峰值力矩、峰值功率、关节做功等体现[9-1]。采集这些数据所需设备主要包括红外高速运动捕捉系统(NOKOV，北京度量科技有限公司)、三维测力台(kistler，瑞士奇石乐)、便携式测速系统(DASLZ-15B，常州德杜精密仪器实力供应商)等，如图 2 所示。

引用格式 王小梅,景会锋.慢跑鞋跟掌落差对人体慢跑状态下肢关节负荷的影响研究[J].中国皮革,2024,53(11):67-72.DOI:10.13536/j.cnki.issn1001-6813.2024-011-013.

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男子铅球运动员最后用力阶段技术特征的运动学分析

关键词

铅球；最后用力阶段；运动学

摘要

最后用力阶段是从左脚落地到铅球出手的过程，是推铅球技术中的最重要的环节，对铅球的运动成绩具有十分重要的作用。本文通过对广州体育学院 3 名男子铅球二级运动员背向滑步推铅球技术进行三维动作捕捉测试，并对最后用力阶段测试结果进行运动学分析，旨在找出铅球最后用力阶段技术的内在规律与本质特征，从而改进与完善运动员的最后用力技术，为铅球技术训练和教学提供理论基础。结果表明:我校男子铅球运动员最后用力阶段技术动作和发力顺序合理，但是仍存在上肢过早抬起，身体左侧支撑、制动效果不好等问题。

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1991

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（ 1）研究对象。本研究的实验对象为广州体育学院 3 名男子铅球二级运动员，3 人均采用右手投掷（以下均用 1 号、2 号、3 号运动员表示）。
（ 2）测试方法。本研究采用 Nokov-Mars2H 三维动作捕捉系统进行采集，采集频率为 340HZ。所有研究对象均穿着黑色的紧身服，并在身体各关节处根据 HelenHayes MarkerSet Placement 标记法结合研究的需要贴上反光点建立人体运动模型后在有效捕捉范围内演示背向滑步推铅球动作。测试前，向运动员对测试要求进行说明。对每名运动员背向滑步推铅球动作各拍摄 3 次，选取成绩最好的一次进行最后用力阶段技术分析。

引用格式 李迪花.男子铅球运动员最后用力阶段技术特征的运动学分析[J].文体用品与科技,2021(05):60-61.

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难美项群水平控腿立转 360°难度动作的运动学分析

关键词

难美项群；水平控腿立转；难度动作；运动学分析

摘要

以体操、艺术体操和竞技健美操三个难美项群中共有的水平控腿立转 360° 难度动作为研究对象，运用高精度光学三维动作捕捉系统，捕获三名不同项目高水平运动员在完成难度的摆臂蹬伸时相和水平控腿转体时相的相关运动学参数，并探讨难美项群不同项目之间的运动学特征。研究表明：1.摆臂蹬伸时相末段形成较大的肩髋扭转角能够提升重心角速度；2.合理的蹬摆技术能够降低转动半径和角加速度，进而减小转动惯量，保证转体时相各身体环节角度的合理性，才能提升重心稳定性和动能转化率；3.相比较而言体操运动员 MO 的水平控腿立转 360° 动作技术，对其他难美项群的旋转类难度练习具有较强的指导意义。

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1993

图 1　受试运动员准备姿态

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2020 年 7 月国际奥委会（IOC）和国际体联（FIG）确立了体操、艺术体操和蹦床为 2024 巴黎奥运会的竞赛项目，在此基础之上提议同时增设双人蹦床、跑酷和竞技健美操三个非奥体操小项，并为其添加具体配额。以体操为依托的各类难美项群运动随着现今国际竞技体育的发展不断壮大，通过技术与艺术的完美结合表现出该项群难和美的显著特征，但技术和难度仍是难美项群的制胜关键。采用 NOKOV 光学三维动作捕捉系统，捕获三名国家级运动健将运动员完成体操、艺术体操和竞技健美操共有的难度动作水平控腿立转 360°的相关运动学参数，并对其进行对比分析，探究各项目平衡柔韧难度之间的技术特征和技术差异。

引用格式 邓俊臣,张舒昊,杜熙茹等.难美项群水平控腿立转 360°难度动作的运动学分析[J].福建体育科技,2021,40(06):53-58.

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女性双肩包负重合理性及其肩带舒适性测试

关键词

产品设计；负重行走；运动医学；背包重量；身体姿势；背带厚度；背负舒适性；脊柱损伤

摘要

目的 (1) 探讨 10% BW(body weight)作为日常负重是否具有科学性。(2) 测试增厚肩带能否有效提升双肩包背负舒适度。方法选取 13 名 22 - 24 周岁的成年女性作为试验对象，分别使用原肩带与加厚肩带，背负重量为 10% BW 的双肩包完成规定运动。使用 NOKOV 光学三维运动捕捉系统测量受试者的躯干角度，并用血压计、运动手环及量表记录其生理数据与主观感受。结果 (1) 背包重量为 10% BW 时，女性受试者的躯干角度与心率、血压较无负重时均无显著性差异；(2) 加厚肩带组的受试者主观疲劳度与局部不舒适度评分结果均显著优于原肩带组。结论 (1) 10% BW 可以作为 22 - 24 岁周岁成年女性的日常安全背负重量，不会对其脊柱与肌肉健康造成严重伤害。(2) 可通过加厚肩带的方法提高背负舒适感，缓解肩颈疲劳。

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1995

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2. 4 数据收集
（1）人体姿态测量
利用 NOKOV 光学三维运动捕捉系统测量静立状态下的人体躯干角度。 如图 2 所示，在受试者的颈部、肋部、髋 部、足部对称粘贴标记点，通过标记点的空间坐标位置计算相应角度。 锁骨、 肋骨、髋骨三处骨性标记点靠近解剖学上的人体第七颈椎（C7）、第 十 二 胸 椎（T12）和 第 五 腰 椎(L5)，可表示人体在矢状面上的躯干屈曲角度， 定义为 CTL 角度。肋骨、髋骨与足部三处标记点可表示以髋骨为轴，人体在矢状面上的躯干前倾角度(Truck Angle)，定义为 TA 角度。 本试验 取左右标记点坐标计算所得角度的平均值为最终结果，以减小标记点因衣物变形等原因产生的位移误差。

引用格式 张未,干静,李颖异等.女性双肩包负重合理性及其肩带舒适性测试[J].人类工效学,2022,28(02):17-22+56.DOI:10.13837/j.issn.1006-8309.2022.02.0004.

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帕金森病患者上肢运动迟缓数字化测评

关键词

帕金森病；运动障碍；上肢；ROC 曲线

摘要

目的采用 3D 动作捕捉系统对帕金森病患者上肢运动迟缓进行数字化测评，以弥补人工测评不足。方法选择 2019 年 6-12 月临床确诊的 19 例帕金森病患者和 10 例同期健康体检者（对照组）为受试对象，在安装有 3D 动作捕捉系统的房间内完成统一帕金森病评价量表第三部分（UPDRS-Ⅲ）测评，受试者拇指和食指固定反光标记物，以同时完成对指这一动作的数字化测评，从中提取最大振幅（amp）、间隔时间（intval）、加速度过零次数（zc）、正向最大速度（v1）和负向最大速度（v2）共 5 项参数；绘制受试者工作特征（ROC）曲线评价 intval、zc 单项或联合测评对帕金森病上肢运动迟缓及对指评分 1 分时的诊断价值。结果帕金森病组 UPDRS-Ⅲ评分（33.79±13.14）分，运动迟缓评分（13.61±5.26）分，上肢运动迟缓评分（6.61±2.65）分，对指评分（1.68±0.78）分。帕金森病组 intval（P=0.001）和 zc（P=0.004）高于正常对照组。intval 和 zc 单项对帕金森病上肢运动迟缓的 ROC 曲线显示，曲线下面积分别为 0.858（95%CI:0.743～0.973，P=0.000）和 0.799（95%CI:0.642～0.955，P=0.008），灵敏度为 0.737、0.921，特异度为 0.900、0.600；intval 与 zc 联合评价，曲线下面积为 0.858（95%CI:0.752～0.964，P=0.001），灵敏度 0.711、特异度 0.100。结论利用 3D 动作捕捉系统能够实现帕金森病上肢运动迟缓的数字化测评，在一定程度上弥补人工测评的缺陷；从中提取的运动参数 intval 和 zc 具有较高的敏感性和特异性，有望成为帕金森病早期筛查的特征性指标。

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NOKOV 度量动作捕捉在研究中的应用摘录

数字化测评过程所有受试者均于装有 3D 动作捕捉系统的房间内完成 UPDRS-Ⅲ量表测评。光学 3D 动作捕捉系统购自 Nokov 公司，包括具有亚毫米捕获精度的相机、特殊软件处理器和小型反光标记点等。相机参数：模型 Mars2H，分辨率 2048×1088，像素 2.2million，频率 340Hz，延迟 2.8ms，视野 56.3°×43.7°，镜头焦距 8mm。受试者拇指和食指粘贴反光标记物，以反射相机发出的红外光，并通过 3D 动态捕捉系统捕捉标记物位置（图 1）。受试者完成对指动作后，移除其反光标记物。收集药物"开"期和"关"期 3D 动作捕捉信息和 UPDRS-Ⅲ评分，帕金森病组 19 例患者共获得 38 组数据。药物"开"期指患者服用多巴丝肼 90min 后或患者感觉药效最佳时，药物"关"期则指未服药、患者状态最差时。以 3D 动作捕捉系统记录 10 个对指周期，同时收集左右手对指数据，有偏侧特征者选取症状严重一侧，无偏侧特征者均选取右侧对指数据；对照组受试者均选取右手对指数据。本研究两组受试者均为右利手。

引用格式 刘培培,于宁波,于洋等.帕金森病患者上肢运动迟缓数字化测评[J].中国现代神经疾病杂志,2020,20(08):721-726.

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跑速和不同内侧楔形鞋垫对男性跑者髌股关节负荷的影响

关键词

内侧楔形鞋垫；髌股疼痛综合征；髌股关节；慢跑；快跑

摘要

研究目的：髌股疼痛综合征是最常见的膝关节过劳损伤之一，并可能会发展为髌股关节炎。内侧楔形鞋垫作为治疗髌股疼痛综合征的非入侵性的方法，经常被用于髌股疼痛综合征的治疗。此前国内外相关研究主要是分析某种内侧楔形鞋垫对髋、膝、踝等关节的生物力学影响进行讨论，而对髌股关节受力特征进行分析的较少，且不同类型内侧楔形鞋垫对髌股关节负荷的影响尚不明确。本文旨在研究不同跑速下不同类型内侧楔形鞋垫对下肢关节运动学、动力学的影响，探讨不同类型内侧楔形鞋垫对髌股关节负荷的影响，以期为跑步爱好者在跑步锻炼过程中预防髌股疼痛综合征提供理论参考。

研究方法：募集 21 名跑步爱好者为受试者，要求其穿着三种内侧楔形鞋垫进行慢跑（3±0.15m/s）和快跑（5m±0.25m/s），使用三维运动捕捉系统（Nokov）和测力台（Betec）同步采集运动学及动力学数据。运用 Cortex 软件对运动学数据进行识别处理，使用逆动力学方法计算出髌股关节接触面积、反作用力、应力等。使用 2×4 重复设计的双因素方差分析确定跑速和内侧楔形鞋垫对髌股关节受力特征的影响。通过单因素方差分析比较不同鞋垫类型是否存在不同，通过配对 T 检验分析比较不同跑速状态是否存在不同，所有显著性标准定为一类误差概率不大于 0.05。

研究结果：双因素方差分析表明，跑速与不同鞋垫类型在运动学与动力学上不存在交互作用。(1) 运动学结果显示，三种类型鞋垫在慢跑时均可以限制髋关节内收角（$p=0.029$、$p=0.019$、$p=0.014$）、踝关节外翻角（$p=0.046$、$p=0.01$、$p=0.042$），此外，前足、全足楔形垫均表现出较低的踝关节跖屈角（$p<0.001$、$p=0.012$）与较高的踝关节背屈角（$p<0.001$）。后足楔形垫表现出较高的膝关节屈曲（$p=0.015$）、穿着鞋垫时最高的踝关节跖屈角（$p<0.001$）与最低的踝关节背屈角（$p<0.001$）；在快跑时，仅有全足楔形垫能够限制髋关节内收趋势（$p=0.024$），后足、全足楔形垫依然能帮助控制踝关节外翻角（$p=0.001$、$p=0.015$），前足楔形垫则减小了膝关节屈曲角（$p=0.044$）。前足楔形垫依旧表现出最高的背屈角度（$p<0.001$），后足楔形垫则为穿着鞋垫时最高的跖屈角度（$p=0.002$、$p=0.015$）。不论鞋垫类型，快跑相较于慢跑均显著增加了髋关节内收角（$p=0.045$、$p=0.004$、$p=0.001$、$p=0.006$）、膝关节屈曲角（$p<0.001$、$p=0.003$、$p=0.006$、$p=0.012$）、踝关节外翻角（$p=0.021$、$p=0.011$、$p=0.035$、$p=0.009$）。（2）动力学结果显示：在慢跑时，后足、全足楔形垫均会导致膝关节内翻力矩（$p=0.025$、$p=0.038$）与膝关节伸展力矩（$p=0.029$、$p=0.050$）的增加。前足楔形垫则有助于降低膝关节内翻力矩（$p=0.021$）与膝关节伸展力矩（$p=0.046$）。后足楔形垫表现出踝关节外翻力矩的降低（$p=0.031$），全足楔形垫则降低了踝关节内翻力矩（$p=0.027$）。在快跑时，仅有后足楔形垫增加了膝关节伸

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展力矩（p=0.046）。不论鞋垫类型，快跑相较于慢跑均表现出较大的髋关节内收力矩（p=0.01、p=0.013、p=0.006、p=0.019）、膝关节内翻力矩（p < 0.001、p < 0.001、p=0.006、p=0.041）以及踝关节外翻力矩（p < 0.001、p=0.001、p < 0.001、p < 0.001）。穿着无鞋垫、前足、全足楔形垫时，快跑相较于慢跑表现膝关节伸展力矩增加（p=0.005、p=0.006、p=0.035）。（3）进一步分析髌股关节受力特征方面，在慢跑时，后足楔形垫相较于无鞋垫与前足楔形垫会增大髌股关节接触面积（p=0.025、p=0.022），表现出更大的髌股关节反作用力（p < 0.001、p=0.03），全足楔形垫仅相较于前足楔形垫表现出更高的髌股关节反作用力（p=0.001）。后足、全足楔形垫相较于无鞋垫（p=0.017、p=0.004）、前足楔形垫（p < 0.001、p < 0.001）均会增加髌股关节应力。前足楔形垫则表现出四种条件下最小的髌股关节反作用力与应力（p=0.026、p=0.012）。不论鞋垫类型，快跑状态相较于慢跑状态均导致了髌股关节接触面积（p < 0.001、p=0.005、p=0.008、p=0.006）、反作用力（p=0.009、p=0.003、p=0.029、p=0.026）、应力的显著增加（p=0.013、p=0.003、p=0.024、p=0.038）。

结论：（1）在慢跑支撑期，跑步爱好者穿着前足内侧楔形鞋垫通过降低膝关节伸展力矩，减少髌股关节反作用力及应力，从而降低髌股关节负荷。穿着后足、全足内侧楔形鞋垫则导致了髌股关节负荷的增加。因此在慢跑时穿着前足内侧楔形鞋垫更有利于帮助避免髌股疼痛综合征的风险，而穿着后足、全足楔形垫可能会增加髌股疼痛综合征的风险；在快跑支撑期，穿着三种类型内侧楔形鞋垫均无法对髌股关节负荷产生显著影响。（2）快跑相较于慢跑表现出更大的髌股关节应力，即增加了髌股疼痛综合征的风险，建议跑步爱好者在运动时可以适当降低跑速，避免高跑速带来的更高的髌股疼痛综合征的风险。（3）三种类型内侧楔形鞋垫对膝关节矢状面角度与髌股关节接触面积的影响较小，从计算模型角度出发，穿着内侧楔形鞋垫造成的髌股关节受力特征的变化可能主要来源于鞋垫对膝关节伸展力矩的影响。

图 2.1-2 实验测试场地示意图

Figure 2.1-2 schematic diagram of the experimental test site

NOKOV 度量动作捕捉在研究中的应用摘录

2.1 研究对象
测试区域上方为 12 镜头红外光点运动捕捉系统(Nokov，中国，200 Hz)，地面中间区域放置三维测力台（ Bertec，美国，1000 Hz）。测试过程中保持测试区域空旷，且预留出足够的助跑距离保证受试者达到跑速要求（如图 2.1-2）。

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跑鞋减震性能对不同慢跑方式下人体膝关节稳定性的影响研究

关键词

跑鞋；减震性能；慢跑方式；膝关节稳定性

摘要

为分析跑鞋减震性能对慢跑状态下人体膝关节稳定性的具体影响规律，本文邀请 15 位具有一定慢跑经验的男性大学生为受试者，借助人体动作捕捉系统等工具对其穿着低、中、高减震跑鞋开展慢跑运动时的膝关节运动学、动力学部分指标进行获取并对比。结果表明：当受试者采用前足落地的方式慢跑时，穿着低减震跑鞋时的膝关节稳定性最佳；当受试者采用后足落地的方式慢跑时，穿高减震跑鞋时的膝关节稳定性最佳。两者相比较，受试者采用前足落地搭配低减震跑鞋的方式进行慢跑时，膝关节的稳定性更好。

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图 3　试验过程

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据有关研究显示，能够反映人体膝关节稳定性的指标主要包括膝关节水平力峰值等动力学参数，以及膝关节角度等运动学参数［4 - 5］。获取这些指标需要应用的试验设备包括 NOKOV 红外人体动作捕捉分析系统(Mars12H，北京度量科技有限公司)；耀龙智能田径运动计时系统(广东耀龙智能科技有限公司)；Bertec 测力台(FP9090 - 15，美国 BE R TEC)。试验设备的现场布置情况如图 1 所示。

引用格式　陈伟.跑鞋减震性能对不同慢跑方式下人体膝关节稳定性的影响研究[J].中国皮革,2024,53(10):60-64+78.DOI:10.13536/j.cnki.issn1001-6813.2024-010-014.

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疲劳对足球运动员专项动作运动学特征的影响

关键词

足球专项疲劳；单脚落地跳；侧切；着地；运动学

摘要

研究目的：足球比赛是高强度、长时间、多方向的间歇性运动项目。在高强度、长时间的比赛过程中，疲劳后带来的神经肌肉功能的下降可能是诱发 ACL 损伤的一个重要的因素。由于其运动形式的独特性导致比赛中疲劳的累积具有一定专项性。目前，基于专项性疲劳模型诱发疲劳导致 ACL 损伤的研究还较少且专项性疲劳导致 ACL 损伤的研究尚无定论。因此，本文旨在分析足球专项体能测试（soccer-specificaerobicfitnesstest，SAFT90）前、后足球运动员进行单脚落地跳和侧切动作时躯干及下肢各关节运动学的差异，进而探究疲劳对足球运动员完成专项动作时可能导致 ACL 损伤的运动学特征。

研究方法：17 名足球专项运动员且运动年限均为 2 年以上为受试者，进行足球专项体能测试（SAFT90）。SAFT90 方案：基于现实足球比赛数据开发的 90 分钟足球比赛模拟协议，可反应出足球比赛的外部负荷及内部负荷。受试者需进行 SAFT90 测试诱发专项性疲劳，并运用 8 镜头 Nokov（中国）红外光点运动捕捉系统（数据采集频率为 200Hz），分别采集单脚落地跳跃（35cm）及侧切动作在疲劳前、后的躯干和下肢各关节的运动学特征数据。运用 Cortex-645.5.0.1579（MotionAnalysisInc，USA）解析软件对运动学数据进行处理及分析得到躯干和下肢各关节的三维角度。利用 2×2 重复测量双因素方差分析观察（疲劳前、后×专项动作）对因变量参数（躯干和下肢各关节运动学数据）的影响，如有交互，后采用配对样本 t-test 确定疲劳前、后和专项动作的差异。所有统计分析应用 SPSS22.0 软件完成，其中显著性标准定为一类误差概率不大于 0.05。研究结果：通过比较专项疲劳和测试动作对躯干和下肢各关节运动学的影响发现，着地时刻膝关节内收外展角存在显著性交互作用（F\[1，15]=5.683，P=0.031）。着地时刻，侧切动作疲劳后表现出较大的膝关节外展角（P=0.017）。另外，不论动作疲劳后均表现出较小的躯干前倾角（P=0.043）、髋关节屈曲角（P=0.003）和膝关节屈曲角（P<0.001）及倾向于足跟着地（P=0.029）；与单脚落地跳相比，不论疲劳前、后侧切动作还表现出较小的躯干前倾角（P=0.008）以及更倾向于足跟着地（P<0.001）等。而在膝关节屈曲角度最大时刻（峰值角度时刻），躯干前倾角度（F\[1，14]=8.43，P=0.012）、髋关节内旋角（F\[1，14]=6.804，P=0.021）、膝关节外旋角（F\[1，15]=12.146，P=0.003）以及髋关节（F\[1，15]=4.782，P=0.045）矢状面关节活动度均具有显著性交互作用。峰值角度时刻，疲劳后仅侧切动作躯干前倾角度减小（P=0.032）；而与单脚落地跳相比，不论疲劳前、后侧切动作表现出较小髋关节屈曲角（P=0.001）和膝关节屈曲角（P<0.001）等。另外，不论动作疲劳后还表现出较大的膝关节矢状面关节活动度（P<0.001）等。

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研究结论：从人体闭合运动链及运动关节耦合方面，着地时刻，两种专项动作均使疲劳诱导后人体以更为直立（僵硬）的着地姿态（较小的躯干前倾角、髋关节屈曲角度和膝关节屈曲角度及峰值躯干前倾角等），这些因素均可能增大 ACL 损伤的风险。着地时刻，不论疲劳前、后侧切动作表现出较小的躯干前倾角及倾向于足跟着地可能造成 ACL 损伤风险大于单脚落地跳。峰值时刻疲劳后，只侧切动作表现出了可能造成 ACL 损伤风险增大的因素（较小的躯干前倾角度）。峰值角度时刻表现出的动作间运动学参数差异可能是由动作特征不同引起的。另外，较大的膝关节活动范围（如较大的膝关节矢状面关节活动度等）也可能造成 ACL 损伤风险增大。

NOKOV 度量动作捕捉在研究中的应用摘录

研究方法：　17 名足球专项运动员且运动年限均为 2 年以上为受试者，进行足球专项体能测试（SAFT90）。SAFT90 方案：基于现实足球比赛数据开发的 90 分钟足球比赛模拟协议，可反应出足球比赛的外部负荷及内部负荷。受试者需进行 SAFT90 测试诱发专项性疲劳，并运用 8 镜头 Nokov（中国）红外光点运动捕捉系统（数据采集频率为 200Hz），分别采集单脚落地跳跃（35cm）及侧切动作在疲劳前、后的躯干和下肢各关节的运动学特征数据。运用 Cortex-645.5.0.1579（MotionAnalysisInc，USA）解析软件对运动学数据进行处理及分析得到躯干和下肢各关节的三维角度。利用 2×2 重复测量双因素方差分析观察（疲劳前、后×专项动作）对因变量参数（躯干和下肢各关节运动学数据）的影响，如有交互，后采用配对样本 t-test 确定疲劳前、后和专项动作的差异。所有统计分析应用 SPSS22.0 软件完成，其中显著性标准定为一类误差概率不大于 0.05。研究结果：通过比较专项疲劳和测试动作对躯干和下肢各关节运动学的影响发现，着地时刻膝关节内收外展角存在显著性交互作用（F\[1，15]=5.683，P=0.031）。着地时刻，侧切动作疲劳后表现出较大的膝关节外展角（P=0.017）。另外，不论动作疲劳后均表现出较小的躯干前倾角（P=0.043）、髋关节屈曲角（P=0.003）和膝关节屈曲角（P<0.001）及倾向于足跟着地（P=0.029）；与单脚落地跳相比，不论疲劳前、后侧切动作还表现出较小的躯干前倾角（P=0.008）以及更倾向于足跟着地（P<0.001）等。而在膝关节屈曲角度最大时刻（峰值角度时刻），躯干前倾角度（F\[1，14]=8.43，P=0.012）、髋关节内旋角（F\[1, 14]=6.804, P=0.021）、膝关节外旋角（F\[1, 15]=12.146, P=0.003）以及髋关节（F\[1，15]=4.782，P=0.045）矢状面关节活动度均具有显著性交互作用。峰值角度时刻，疲劳后仅侧切动作躯干前倾角度减小（P=0.032）；而与单脚落地跳相比，不论疲劳前、后侧切动作表现出较小髋关节屈曲角（P=0.001）和膝关节屈曲角（P<0.001）等。另外，不论动作疲劳后还表现出较大的膝关节矢状面关节活动度（P<0.001）等。

引用格式 郭浩,刘瑞瑞,王广宇等. 疲劳对足球运动员专项动作运动学特征的影响[A]. 中国体育科学学会.第十一届全国体育科学大会论文摘要汇编[C].中国体育科学学会：中国体育科学学会，2019：2.DOI：10.26914/c.cnkihy.2019.029915.

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铅球二级运动员最后用力阶段运动学分析

关键词

核心动态稳定性训练；推铅球技术动作；推铅球成绩

摘要

背向滑步推铅球是技术相对较复杂的运动项目，要求运动员在投掷过程中保持重心的稳定和身体姿势的控制。核心动态稳定性训练作为体能训练的一种，能较全面的提升个体在运动中核心肌群的稳定能力和增加运动肌群的力量。本研究针对推铅球教学训练中易忽视的核心稳定性训练，探索核心动态稳定性训练对推铅球教学效果的影响，目的是验证核心动态稳定性训练对推铅球技术掌握和成绩的提高是否有促进作用。本文通过文献资料法、专家访谈法、实验法和数理统计法等研究方法。结合背向滑步推铅球项目的技术原理以及运动学规律，设计出一套核心动态稳定性训练方案，将其应用在推铅球技术教学课中，实验结束后，对实验对象推铅球成绩和动作技术进行考评并分析。同时为了更好的对教学效果进行检验，采用 Nokov-Mars2H 三维动作捕捉系统对实验对象进行运动学数据采集，对所获得的运动学数据进行对比分析。结果如下：1，专项素质与稳定性测试：实验前后实验组与对照组 30m 跑无显著性差异（$p > 0.05$），但立定跳远、原地推铅球、原地推实心球、一分钟仰卧起坐及 FMS 得分实验前后实验组提升幅度大于对照组（$p < 0.05$）。2，推铅球成绩和技评得分：实验后，实验组推铅球成绩平均值比对照组高 0.37m，差异显著（$p < 0.05$）。技术评分两组实验对象握持球和预备姿势无显著性差异（$p > 0.05$），滑步阶段、转换阶段、最后用力和维持平衡阶段得分实验组比对照组提升显著（$p < 0.05$）。3，运动学数据分析：实验验后实验组各阶段的关节角度变化更趋于理想值，重心水平速度实验组比对照组提高显著（$p < 0.05$），出手速度和出手角度更符合技术要求。出手高度两组实验对象平均值无差异（$p > 0.05$）。通过分析得出以下结论：1，通过核心动态稳定性训练，可以促进学生专项素质提升，能有效提升核心力量，提高推铅球出手力量，加快动作速度，保证动作技术的连贯性。2，核心动态稳定性训练对推铅球成绩提高有较好帮助，试验后实验组学生铅球平均成绩更优。3，在滑步阶段，实验组学生重心水平速度较快，左腿摆动较积极，重心起伏程度较低，滑步时间较短，滑步距离较大。整个滑步技术更符合教学要求。4，在过渡阶段，对照组学生左腿下落较慢，建立起稳定的双支撑平面效果较差，对照组学生右髋上抬幅度值较大，左侧支撑技术不理想，右腿下落时右踝角度较大，没有在右腿落地时迅速的内扣及蹬伸，导致过渡阶段的水平速度损失较大。5，在最后用力阶段，实验组学生铅球速度与重心速度差值小于对照组，“人-球”整体效果更好，实验组学生出手速度和出手角度更符合教学技术要求，各项指标更趋于理想效果。

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NOKOV 度量动作捕捉在研究中的应用摘录

本实验以 12 台 Nokov 牌动作捕捉仪器，机高 2m，有效捕捉范围面积为 30m2。截取运动员投掷过程中最后用力瞬间膝关节角度变化进行比较并加以讨论分析。

引用格式 邹新貌,段及丞,朱华杰.铅球二级运动员最后用力阶段运动学分析[J].文体用品与科技,2021(21):73-74.

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前交叉韧带重建后急停起跳过程中膝关节应力的有限元分析

关键词

前交叉韧带重建；急停起跳；股骨软骨；半月板；应力；有限元分析

摘要

背景：已有研究分析了前交叉韧带重建患者术后完成不同动作时健患侧运动学、动力学等运动特征，假设前交叉韧带重建术后患者在完成急停起跳动作时健侧前交叉韧带 von Mises 应力较患侧高，半月板和股骨软骨的 von Mises 应力较患侧低。目的：通过探究前交叉韧带重建患者健患侧膝关节软组织的应力响应特征，以期为降低该人群发生前交叉韧带二次损伤及慢性膝关节骨性关节炎等继发性损伤提供参考。方法：运用红外光点运动捕捉系统(NOKOV)和测力台(Bertec)采集前交叉韧带重建患者急停起跳时膝关节运动学和动力学特征，通过欧拉角计算方法和逆动力获得膝关节三维角度和三维力矩参数，并将膝关节三维角度和力矩作为边界和加载条件分别载入健患侧膝关节有限元模型，进行数值仿真，比较健患侧膝关节内部结构在实际运动载荷下的应力分布情况。结果与结论：(1)在水平向后第一地面反作用力峰值时刻，患侧膝关节屈曲角、内收角明显大于健侧，且健侧垂直地面反作用力高于患侧。此外，健侧垂直地面反作用力峰值出现在急停起跳阶段的 4%-6%，而患侧出现在急停起跳阶段的 15%-17%，表现出健侧腿较患侧先着地的运动模式。(2)有限元分析显示健侧前交叉韧带 von Mises 应力峰值高于患侧(28.47 MPa vs. 13.18 MPa)，且健侧最大应力出现在前交叉韧带后束部位，而患侧分布于前交叉韧带前侧股骨端；此外，患侧股骨软骨(12.16 MPa vs. 5.342 MPa)和半月板(17.35 MPa vs. 16.18 MPa)von Mises 应力峰值均大于健侧，对应的最大应力峰值分别位于股骨远端关节软骨外髁边缘处和外侧半月板前角边缘。(3)有限元模拟得出前交叉韧带重建患者健侧发生前交叉韧带损伤风险较患侧前交叉韧带二次损伤风险可能更大，进一步由于患侧股骨软骨和半月板产生较高的应力可能会加重膝关节骨性关节炎的发展；研究结果提示前交叉韧带重建患者进行康复训练时不仅需关注患侧的康复训练，健侧异常的运动模式和代偿反应亦不容忽视。

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图 1 | 急停起跳动作示意图

Figure 1 | Stop-jump maneuvers

NOKOV 度量动作捕捉在研究中的应用摘录

受试者穿着实验室提供的紧身上衣、短裤及统一的实验运动鞋，在测试前进行充分的准备活动，并由同一操作人员为受试者粘贴 29 个反光标志点，位置参考张美珍等[14] 的研究。测试动作为急停起跳[15](见 图 1)，动作要求受试者在离测力台 5-10 m 处开始助跑，在距测力台还有一步时，两足同时跳到测力台台面后急停，然后立刻尽全力垂直向上起跳并落地。测试过程通过 Witty-Manual 光栅测量受试者完成动作的助跑速度，速度在(3.5±0.2) m/s 内为 1 次有效数据[16-17]。使用 12 镜头红外光点运动捕捉系统(200 Hz，Nokov Mars2H，中国) 采集受试者各标志点坐标，利用三维测力台(1 kz，Bertec，美国) 同步采集受试者动力学数据，要求受试者双脚均落在测力台内，共采集 3 次有效数据。

引用格式 刘艺辉,闫可,张力文等.前交叉韧带重建后急停起跳过程中膝关节应力的有限元分析[J].中国组织工程研究,2023,27(35):5701-5706.

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浅析标枪二级运动员交叉步环节运动学分析

关键词

标枪；交叉步；膝关节；角度变化

摘要

本文通过采用 15 台动作捕捉仪器采用定位捕捉运动员的关节角度变化来分析我校二级男女标枪运动员在投掷标枪中交叉步技术中的运动学变化，并且与世界优秀男女标枪运动员投掷交叉步环节运动学变化比较并进行讨论与分析。希望运动员了解自身的不足达到查缺补漏继续提高运动技术，也为其他教练员提供一种新的训练手段。本文运用 15 台动作捕捉仪器全方位捕捉标枪运动员在投掷交叉步环节中的运动学变化并且完成相应数据的统计与处理。从运动学角度对标枪二级运动员交叉步关节角度、后倾角度的变化进行了分析,在结果中发现我校二级男女标枪运动员核心力量较差、上下肢协调相对较弱，动作技术不够娴熟，下肢制动力量不够完美且控制力不足。

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NOKOV 度量动作捕捉在研究中的应用摘录

2、研究对象与方法
2.2 、研究工具
本实验以 15 台 Nokov 牌动作捕捉仪器，机高 2m，有效捕捉范围面积为 100m2。

引用格式 杜松.浅析标枪二级运动员交叉步环节运动学分析[J].文体用品与科技,2020(21):70-72+91.

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人机工效学座椅参数对人体下肢生物力学特性影响研究

关键词

座椅参数；运动生物力学；关节力矩；肌肉力矩；ADAMS 仿真

摘要

在人机工效学座椅参数的设计中,大多数研究及评价方法都是基于静态稳定姿势,而从静坐到站立这一动态过程往往被忽视。在这一短暂动态过程中,关节所受力和力矩起伏较大,关节磨损也更加明显。因此,对坐到站运动过程中的下肢生物力学特性影响研究显得尤为重要。在座椅参数中,座椅高度和坐深会对下肢生物力学产生极大的影响,现有的研究中,针对坐高的研究相对较多,但对于坐深的研究很少,也并未将坐高和坐深结合进行研究。因此,本研究从坐高和坐深角度出发研究坐立运动对下肢生物力学特性的影响。本文通过建立坐立运动过程数学模型,再配合实验研究,分析坐高和坐深对下肢生物力学的影响。本文的研究内容如下:(1)坐立运动过程及建模方法。整理了现有研究中坐立运动阶段划分方法、生物力学模型分类以及数学模型的建模方法,在此理论基础上提出自己的建模方法和研究思路。(2)坐立运动过程运动学及动力学建模。将人体简化为头臂-躯干、髋关节、大腿、膝关节、小腿、踝关节和足构成的三连杆生物力学刚体模型,从静态效应和惯性效应两方面考虑计算关节力矩。另外,进行连接段建模,分别对足部、小腿和大腿各连接段建立水平轴和垂直轴上的动态力平衡方程和力矩平衡方程,计算关节反作用力和肌肉力矩。(3)坐立运动过程仿真分析。根据人体体段划分方法划分的 15 个人体体段,在 SolidWorks 三维建模软件分别建立人体 1 5 个体段三维刚体模型,并在 ADAMS 仿真软件进行人体运动仿真,将仿真输出踝关节、膝关节和髋关节力矩与第三章数学模型计算的各关节力矩进行对比,验证数学模型的正确性。(4)实验及结果分析。搭建了高度可调节实验座椅、一维力平台和三维力平台,再配合动作捕捉对招募的 22 名受试者进行坐立运动实验,通过数据处理获得受试者在坐到站过程中的各关节实时角度以及外力数据,最后将实验数据带入到建立的数学模型中计算各关节力矩、关节反作用力和肌肉力矩,根据计算结果分析座椅参数对坐立运动过程下肢生物力学特性的影响。论文研究成果表明,各关节力矩、关节反作用力和肌肉力矩都会随着座椅高度的增加而减小,踝关节力矩随着坐深的增加而减小,髋关节力矩随着坐深的增加而增大,而坐深对膝关节力矩和各关节肌肉力矩以及各关节反作用力的影响在座椅高度为 100%腿高上下存在相反的趋势,总体上来说,座椅高度为 100%腿高时,坐深对其的影响较小。论文的研究结果及数学模型可为座椅设计、老年人下肢力量及平衡研究、下肢康复坐立运动训练和坐立辅具设计提供参考。

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图 5-1 动捕实验室场景图

NOKOV 度量动作捕捉在研究中的应用摘录

采用 NOKOV 度量光学三维动作捕捉设备、可升降实验座椅、一维力平台和三维力平台等设备搭建了人体坐立运动实验台。人体运动学数据可以通过实验室的 NOKOV 度量光学三维动作捕捉设备获取， 对人体在坐到站动态过程进行分析研究，基于 NOKOV 度量光学三维动作捕捉设备和自制力板（三维力板、一维力板）采集受试者在不同坐高和坐深情况下整个运动过程中的实时运动学和动力学数据。分析整个运动过程，建立踝关节、膝关节和髋关节力矩数学模型；另外通过连接段模型，对各连接段及足部、小腿和大腿分别建立水平方向和垂直方向上的动态力平衡方程和力矩平衡方程，计算各关节净肌肉力矩。

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人体坐立运动的膝关节动力学研究

关键词

关节力矩；地面反作用力；坐立运动；动力学模型；动作捕捉

摘要

坐立运动是人体最常见的运动行为之一，膝关节是人体坐立运动的主要承力关节，因此进行坐立运动过程的膝关节动力学研究具有重要意义。基于力矩平衡原理对坐立运动的膝关节动力学进行分析，结合光学动作捕捉和六维支撑力测试所得数据，计算求得膝关节力矩曲线。为了验证实验数据和动力学分析的准确性，建立人体模型，根据实验数据拟合角度和角速度多项式方程，进行坐立运动的膝关节动力学仿真。结果显示计算数据和仿真数据在范围和变化趋势方面一致。综合膝关节力矩变化规律，揭示了膝关节力矩与地面反作用力的关系。坐立运动中膝关节力矩和地面反作用力成正比关系，比值为 5 ~ 6，且由坐到立过程中，加速度先增大后减小最后反向增加，力矩最大值发生在膝关节夹角约 140°时，而由立到坐过程中，力矩在初始阶段最大。坐立运动的膝关节动力学研究结果有益于坐立康复辅具的优化设计及力反馈控制，并可为膝关节康复训练提供理论指导。

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图 2　坐立动作实验场地布置图

Fig.2　The layout of sitting-standing action test

NOKOV 度量动作捕捉在研究中的应用摘录

1.2 动作捕捉与反力采集实验
实验过程中，动捕系统采集到的数据难免会出现噪声点和缺失点，使用 Nokov 公司的 Seeker 软件进行数据处理\[27]，基于各点的位置建立人体棍棒模型，其运动过程为一个完整的坐立周期，经对比静止值和动态值，偏移位置在可控范围内。所获定位点的位置、速度、加速度用作理论分析变化量，处理后代入膝关节力矩公式中求解力矩。髋关节、膝关节和踝关节处角度数据将用于后续的仿真分析。

引用格式　苏鹏,王思锴,张力等.人体坐立运动的膝关节动力学研究[J].生物医学工程学杂志,2022,39(05):982-990.

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任务驱动教学法在拉丁舞前进步接平转技术教学中的实验研究

关键词

任务驱动教学法；拉丁舞；教学效果；平衡；动作分析；评价

摘要

近些年，随着我国教育改革的不断深化，许多学者在课堂教学方法方面进行深入研究。任务驱动教学方法作为建立在建构主义理论基础的教学方法，突出学生主体地位。虽然体育舞蹈教育教学研究取得一定的成果，但如何依据新时代教育改革指导，在课堂教学过程中面对着"教学内容"和"学生"两个主体，运用适当有效的教学方法，使现代化信息技术与体育教学深度融合，让学生能更好地学习和收获体育舞蹈知识、技能等，这是值得进一步探讨与实证研究。本文采用文献资料法、专家访谈法、实验法、数理统计法、逻辑分析法等研究方法，通过将任务驱动教学法运用在高校拉丁舞教学中，对教学内容进行分析，结合拉丁舞项目特点进行教学设计，以任务驱动教学法在高校拉丁舞教学效果为研究对象，把广州体育学院体育舞蹈选修课的学生，随机分组为对照组（女生 19 人）、实验组（女生 20 人）作为实验对象，其中对照组运用传统教学方法，实验组运用任务驱动方法进行教学，经过 8 周的教学实验后，通过对两组进行教学效果的对比和分析，研究结果显示：

（1）在教学实验前，两组间坐位体前屈和平衡反应比较无显著性差异；在实施教学实验后，两组内的坐位体前屈和平衡反应成绩均有显著提高（$P<0.01$），两组间身体素质成绩比较无显著性差异，但与对照组相比，实验组的平衡反应成绩提高较多。

（2）教学实验后，两组间的拉丁舞动作技术评分比较无显著性差异，但与对照组相比，实验组的评分较高。

（3）教学实验后，在分析两组学生技术动作重心位移变化中，与对照组相比较，实验组在 X 轴方向上偏移量较少，Z 轴方向上垂直位移变化幅度较少，在平转阶段身体躯干接近垂直，在结束阶段 Y 轴方向上速度较少，整体反映出对身体重心控制较好和动作流畅稳定，与动作评分结果有较高的吻合度。

结论：

（1）任务驱动教学法采用任务的形式能顺利开展教学，对相应的技术动作进行细分模块和任务学习，学生能较好的接受并完成任务，并结合动作分析，促进对技术动作的学习，对培养学生学习的主动性有积极作用。

（2）任务驱动教学法对促进学生学习拉丁舞，改善身体平衡素质更有积极作用，在拉丁舞动作技术教学中能较好地让学生掌握技术动作，主要体现在身体重心的控制能力和动作的稳定性。

（3）拉丁舞教学中对动作技术的重心位移、速度和躯干角度进行运动学分析比较，对技术动作

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的客观评价与定量有积极参考意义。

图 10 Nokov 三维动作捕捉设备（部分）

注：图 10-1：数字捕捉镜头；图 10-2：数据交换器；10-3：电脑操作平台；图 10-4：“T”型棒；图 10-5：marker 点；图 10-6：数字捕捉镜头连接线；图 10-7：数据传输线；图 10-8：数字捕捉镜头支架。

NOKOV 度量动作捕捉在研究中的应用摘录

本实验使用三维动作捕捉设备（Nokov，中国）（图 10）对动作进行运动学分析，16 个镜头可识别采集的空间位置分布如图 11 所示。对所获得动作数据进行处理和后期分析等工作，可分析的数据有重心的变化、加速度、关节角度、点速度和两点间距离。

引用格式 杨贺贺.任务驱动教学法在拉丁舞前进步接平转技术教学中的实验研究[D].广州体育学院，2021.DOI：10.27042/d.cnki.ggztc.2021.000069.

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失重环境下航天员作业轨迹规划研究

关键词

航天员上肢模型；轨迹规划；多目标优化；运动捕捉；

摘要

随着航空航天技术的发展,计算机、自动化等各个领域的进步,人们在航空航天领域方面的研究越来越广泛,对航天员各方面的要求也越来越高。航天员不仅需要进入太空,而且需要在太空中完成各种复杂的任务,采用高效的作业方式会使任务操作更加安全,因此针对航天员在太空中如何以最佳方式执行任务的研究变得尤为重要。本文通过计算机仿真研究对航天员的操作训练提出了一种适宜可行的方法。针对一次舱外活动搬运大型载荷任务,建立航天员冗余七自由度上肢模型；在运动学、动力学基础上,完成对执行特定任务的轨迹规划；提出一种有关时间、能量、冲击的多目标优化方法,并在关节空间中完成多目标轨迹优化,最后通过运动捕捉系统对地面上航天员的训练进行运动捕捉并评价分析,本文主要研究内容如下:

通过对人体解剖学及生理学的分析,分别对腕关节复合体、肘关节复合体和肩关节复合体进行细致阐述。针对穿着航天服下的人体手臂生理结构,抽取双臂的等价运动链,分别采用 D-H 法和 GABP 神经网络法完成对航天员手臂正、逆运动学的分析,并进行仿真验证。考虑充压航天服及太空失重环境对运动的影响,提出航天服关节阻力矩迟滞模型,并利用拉格朗日法建立航天员上肢的动力学模型。通过简化的三自由度手臂模型,对比分析未着服、着服未充压和着服充压下的航天服对航天员运动的影响。

采用蒙特卡洛法对着服航天员单臂的工作空间,双臂协作工作空间进行求解。针对操作空间和关节空间分别采用五次多项式插值法及 4-1-4 次多项式插值法进行轨迹规划,实现始末无冲击的运动。针对一次搬运载荷任务采用 7 次 B 样条曲线法在关节空间构造轨迹,建立了以时间、能量、冲击为目标的多目标优化函数。采用非支配排序遗传算法（NSGA-II）对航天员作业轨迹进行了多目标优化,根据模糊隶属度在 Pareto 解集中选取最优解,得到所需的运动轨迹,该算法可以在减少时间的基础上同时减少能量和冲击。

在运动捕捉系统（NOKOV）下进行操作训练模拟实验,以最优轨迹为标准进行仿真示教,采用动作捕捉系统对实验人员训练动作进行捕捉,通过 seeker 软件进行数据处理,得到每次运动过程中所消耗的时间、能量及冲击,最后通过评价函数对每次训练过程进行评价分析,得出每组运动评价分数,根据评价标准值及示教过程调整位姿进行后续反复训练。

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NOKOV 度量动作捕捉在研究中的应用摘录

第六章：实验仿真验证。采用运动捕捉系统（ NOKOV）对执行特定任务时的实验人员进行运动捕捉，求得运动过程中所消耗的时间、能量及冲击，与上述按照最优运动轨迹运动时的结果进行对比，通过评价函数完成对动作进行评估。
北京度量科技有限公司 NOKOV 动作捕捉系统\[58] ，由镜头、反光标识点、云台、镜头连接线、镜头固定装置等附件构成。主要采用高性能的红外镜头捕捉安装在被测量物体上的反光标示点，构建三维数据的动作采集与分析系统，对采集的数据通过软件 Seeker 进行分析处理，广泛应用于机器人、无人机、医疗康复、运动仿真、虚拟现实等多个领域，本节技术路线如图 6.1 所示。
通过示教的方式，采用运动捕捉系统（ NOKOV）对执行特定任务时的实验人员进行运动捕捉，计算过程中所消耗的时间、能量及冲击，通过评价函数对动作进行评估。

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数字化视角下短跑动作训练虚拟仿真系统设计

关键词

数字化视角;短跑运动;动作训练;虚拟仿真系统

摘要

文章从数字化视角下短跑动作训练系统的基础需求入手,构建了一种短跑动作训练虚拟仿真系统。 该系统由输入层、功能层和可视化层等结构组成,主要功能包括短跑动作捕捉、训练方案生成、回 放与评价等。 对该系统的应用情况进行测试,结果表明:该系统可以在较低的时间延迟下为运动员提 供完善的动作捕捉和虚拟训练功能,具有一定的实用性。

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（a）动作捕捉功能　（b）训练方案生成　（c）训练资料调阅

图 3　系统功能实现

NOKOV 度量动作捕捉在研究中的应用摘录

为对比组,以搭建的系统为实验组进行系统性能测试\[9-10];以相同的 NOKOV 动作捕捉系统(北京度量科技有限公司)和体感器(深圳市探奇科技有限公司)作为本次测试的硬件设备,尽可能减少测试影响因素;以同一批短跑运动员为研究对象,测试其应用不同系统时的系统延迟,得到本次搭建虚拟仿真系统的性能测试结果。

引用格式　付海芳.数字化视角下短跑动作训练虚拟仿真系统设计[J].无线互联科技,2024,21(19):75-78.

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田径综合训练鞋触地生物力学特征与人体损伤关系研究

关键词

田径运动； 综合训练鞋； 触地方式； 人体损伤

摘要

邀请 20 位田径运动员作为受试者， 选择鞋中底邵氏硬度分别为 5 2、 6 2、 7 2 的综合训练鞋，对受试者穿着不同训练鞋采取前掌落地、 后足落地两种不同落地方式奔跑时的触地阶段生物力学特征进行分析， 总结了不同状态下田径综合训练鞋、 触地方式等与人体运动损伤之间的关系。结果表明，当综合训练鞋邵 氏硬度高时，采取前脚掌触地方式更不容易出现运动损伤；反之，当综合训练鞋邵氏硬度低时，采取后足 触地方式更不容易出现运动损伤。

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人体下肢生物力学特征的获取通常需要借助运动捕捉系统、测力台等。图 2 所示为本试验所需设备的基本布置情况其中，NOKOV 运动分析系统（Mars12H，北京度量科技有限公司）主要负责对受试者慢跑状态下的生物力学参数进行捕捉；耀龙智能田径运动计时系统（广东耀龙智能科技有限公司）负责对受试者的奔跑速度进行控制；Bertec 测力台（FP4060 - 07 - 1000，美国 BERTEC 公司）负责对受试者慢跑支撑期内的力、力矩、扭矩等数据进行获取。

引用格式 仝丽君.田径综合训练鞋触地生物力学特征与人体损伤关系研究[J].中国皮革,2024,53(12):81-85.DOI:10.13536/j.cnki.issn1001-6813.2024-012-015.

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同步性联合运动中对他人运动预测的认知神经基础

关键词

同步性联合运动；合作意图；他人运动预测；任务线索；反馈线索

摘要

人与人之间在行为上的同步性是一种常见的合作形式。同步性联合运动指在社会互动过程中个体间为实现动作在时间上同步的一种合作性运动。

在同步性联合运动中，对他人的运动预测是实现个体间动作同步的关键。预测的线索主要来自于他人的目标信息和他人的运动信息。共同编码理论主张，基于他人的目标信息所形成的他人任务表征是运动预测的前提，其在联合运动中起主导作用，引导基于运动信息的预测加工。层级预测模型主张，他人的运动信息中的反馈线索包含了动作结果的信息，其对运动预测有着迭代优化作用。那么，哪一种观点更符合同步性联合运动中对他人运动预测的认知加工机制？基于不同线索所产生的运动预测如何影响个体间动作同步？其神经基础是什么？

本论文通过三项研究共 8 个实验，采用联合触点任务，以对此问题进行探讨

综合研究结果，在本论文研究条件下，可得出以下结论：

（1）在同步性联合运动中，个体基于合作意图调节自我-他人相关过程，预测他人的动作并调整运动表现。

（2）同步性联合运动中个体间动作同步的实现需要借助以下两条预测路径：他人的目标信息和他人的运动信息，且二者作用于同步性联合运动的影响方式不同。

（3）任务线索、反馈线索在同步性联合运动中对他人运动预测的作用不同。利用反馈线索中他人动作的时间预测他人运动，其在同步性联合运动中起关键作用。

（4）颞顶联合区普遍参与了同步性联合运动中个体间的社会互动过程。基于任务线索对他人的运动预测与前运动辅助运动区的神经活动有关，基于反馈线索对他人的运动预测与背外侧前额叶、前运动辅助运动区的神经活动有关。

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1.2 方法
（ 7）实验设备
实验设备。运动捕捉系统，设备为北京度量科技生产的 Nokov 光学三维运动捕捉系统（ Mars 4H， NoKovCorporation， Beijing， China)，采样率为 100Hz。

引用格式 陈怡馨.同步性联合运动中对他人运动预测的认知神经基础[D].天津师范大学，2021.DOI：10.27363/d.cnki.gtsfu.2021.000748.

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五行通背拳"周天状"动作下肢肌肉协同与重心稳定性的关系研究

关键词

重心稳定性；肌肉协同；五行通背拳

摘要

研究目的：运用运动生物力学的方法与手段对五行通背拳"周天状"状法动作运动过程中髋膝踝关节角度、下肢肌肉协调贡献与人体重心变化特点进行分析，揭示重心稳定性与下肢肌群协同变化的关系，为五行通背拳周天状提高人体动态稳定性的功能提供实验证据，为其锻炼方法的推广提供理论依据，为跌倒的预防提供科学锻炼方式。

研究方法：本研究以五行通背拳第四代传人为测试对象，运用 Nokov 运动捕捉系统、AMTI 测力台及 Biovision 多导运动生物电遥测记录分析系统同步对运动过程中的运动生物力学参数变化进行采集。受试者完成 6 组五行通背拳"周天状"动作，精选 3 组动作的数据进行分析。由 Nokov 运动捕捉系统中自带的 Seeker 软件获取受试者髋膝踝在矢状面、冠状面、水平面的关节变化角度及人体重心 (center of mass,COM) 等运动学参数；由 AMTI 测力台获取足底压力中心 (Center of Pressure,COP）在前后、左右和上下方向等动力学参数；运用 V3d 软件进行仿真建模，获取下肢各个关节的三维受力参数；由 Biovision 多导运动生物电遥测记录分析系统获取下肢臀大肌、股直肌、股内侧肌、股外侧肌、股二头肌、胫骨前肌、腓内侧肌、腓外侧肌八块肌肉的 IEMG、RMS、肌肉贡献率及膝踝关节肌肉共激活指数等生物学参数。采用描述性分析对五行通背拳周天状的动作特点进行描述，采用独立样本 T 检验对运动过程中人体重心（center of mass,COM）和足底压力中心（Center of Pressure,COP）数据的差异性进行对比分析，运用皮尔逊相关分析法对肌肉协同和重心稳定性的关系进行分析，采用曲线估计建立二者的曲线回归方程，对二者关系进行量化，最后用 origin 软件进行曲线回归方程的绘图处理。

研究结果：（1）狮子滚球的人体重心摇径面积在前后方向摇径最大为 0.37m2，摸鱼式的人体重心摇径面积在左右方向最大为 0.34m2，摇山晃海的重心晃动幅度在左右方向最大为 0.27m；三个动作 COP 变化呈对称性特点，且摇径面积在 0.01m2-0.02m2 之间。

（2）狮子滚球动作在单个运动周期内，臀大肌与胫骨前肌在七块儿肌肉中贡献最大，分别为 34.9%，11.1%；股二头肌与股直肌的共激活指数在膝关节、踝关节各肌肉中激活指数最高，为 97%。摸鱼式动作股外侧肌、胫骨前肌贡献率最高，分别为 17%、10%；股二头肌与股直肌的肌肉共激活指数为 87%，胫骨前肌与腓肠外侧肌的共激活指数为 84%。摇山晃海动作股二头肌与股外侧肌贡献率最高为 18.03%，18.87%；胫骨前肌与腓肠外侧肌的肌肉共激活指数最高，为 93%。

（3）狮子滚球动作在第一阶段中 COG 的晃动指数在左右、上下方向与膝踝关节共激活指数关系最为显著，其中，在左右方向上与左踝、右膝关节肌肉共激活指数存在极强负相关关系，分别

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为-0.97、-0.95；在上下方向上与右侧踝关节存在极强相关关系为 0.83，即右踝关节共激活指数越高，COG 向左移动距离越大。在第二阶段中 COG 晃动指数在左右、前后方向与膝踝关节肌肉共激活指数关系最为显著；在左右方向，与左踝、右踝关节肌肉共激活指数存在极强相关关系，分别为 0.94、-0.80。

（4）摸鱼式动作运动过程中 COG 的晃动指数在第一阶段中在左右方向与左、右膝关节肌肉共激活指数存在极强相关关系，分别为 0.86、-0.99。在第二阶段中，在左右方向与左膝、右踝关节肌肉共激活指数存在极强相关关系，分别为 0.86、-0.98；在前后方向与右膝、右踝关节肌肉共激活指数存在极强相关关系，分别为 0.94、-0.87；在上下方向与右膝、右踝关节肌肉共激活指数存在极强相关关系，分别为 0.76、-0.94。在第三阶段与膝、踝关节肌肉共激活指数为弱相关关系。

（5）摇山晃海动作第一阶段的 COG 晃动指数在左右方向与膝踝关节肌肉共激活指数存在极强相关关系，在前后方向与膝踝关节肌肉共激活指数存在强相关关系，在上下方向与膝踝关节肌肉共激活指数存在弱相关关系；第二阶段的 COG 晃动指数在左右方向与膝踝关节肌肉共激活指数存在极强相关关系，在前后方向与左侧膝踝关节肌肉共激活指数存在强相关关系，在上下方向与右侧膝踝关节肌肉共激活指数存在极强相关关系。

（6）狮子滚球动作在运动过程中左右侧膝踝关节共同配合，促使 COP 进行移动，在第一阶段左右方向上，右膝关节肌肉共激活指数与左侧 COP 存在极显著关系，为 0.93，右踝关节肌肉共激活指数与右侧 COP 存在极显著负相关关系，为 0.83；在前后方向上，左侧 COP 与左踝、右踝关节肌肉共激活指数与存在极显著关系，分别为 0.95、0.76；右侧 COP 与左踝、右膝关节肌肉共激活指数与存在极显著负相关关系，分别为-0.65、-0.83。在第二阶段，左侧 COP 在左右方向与右膝关节肌肉共激活指数存在极显著相关为 0.93，在前后方向与左踝关节存在极显著相关关系为 0.83；右侧 COP 在左右方向与左膝关节肌肉共激活指数存在极显著相关为 0.92，在前后方向与右膝关节肌肉共激活指数存在极显著负相关关系为 0.83。

（7）摸鱼式动作在第一阶段运动过程中，左侧 COP 在左右方向的晃动指数与左右膝关节肌肉共激活指数存在极强相关关系，为-0.91、0.92。在第二阶段，左侧 COP 在左右方向的晃动指数与左踝、右膝关节肌肉共激活指数存在极强相关关系，为-0.95、0.99；前后方向与左右方向相同，为 0.84、-0.88。在第三阶段右侧 COP 在左右方向与左膝关节肌肉共激活指数存在极强相关关系，为 0.74；在前后方向与右侧膝关节肌肉共激活指数存在极强正相关关系，为 0.72.

（8）摇山晃海动作在第一阶段运动过程中，双侧 COP 在左右、上下方向与右踝关节肌肉共激活指数存在极强相关关系，分别为 0.82、0.84、0.90、0.75。在第二阶段运动过程中，双侧 COP 在左右、上下方向与右膝关节肌肉共激活指数存在极强相关关系，分别为 0.87、0.89、-0.94、0.80。

研究结论：周天状动作在运动过程中，膝、踝关节肌肉共同激活协同发力，促使髋、膝、踝关节协调运动完成动作，在增强力量的同时提高各关节的协调能力，提高重心移动能力，从而使下肢的姿势控制能力提高，通过练习可以提高人体动态平衡能力，进一步预防跌倒的发生，此外各个

动作特点不同，可以针对不同人群的需求进行推广。

图 3-1　场地布置图片

NOKOV 度量动作捕捉在研究中的应用摘录

采用北京度量科技有限公司的 Nokov 运动捕捉系统，有 28 个摄像头，采集分辨率设置不小于 400 万像素，最大分辨率下的最大采集频率为 180Hz 对五行通背拳第四代传承人关博教授进行拍摄，获得关节角度、角速度、测试时间等数据。

引用格式 卫文文. 五行通背拳"周天状"动作下肢肌肉协同与重心稳定性的关系研究[D].东北师范大学，2023.DOI：10.27011/d.cnki.gdbsu.2023.001425.

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下肢制动能力训练对羽毛球主项选修班学生向前移动步法影响的实验研究

关键词

主项选修；下肢制动能力；制动；向前移动步法

摘要

羽毛球运动作为隔网对抗性项目，具有场地小、速度快、移动次数多等特点，步法技术中，制动动作既是上一个步法的结束，又是下一个步法的开始。但在日常训练与步法教学当中，对起动力量、爆发力的练习较多，制动力量训练的提及却很少。因此，本文根据现代羽毛球竞赛中步法技术特征和课堂教学特点，提出下肢制动能力训练方法。

本文采用文献资料法、专家访谈法、问卷调查法、实验法、数理统计法等方法，以广州体育学院 2019 级体育教育专业羽毛球主项选修 1、2 班各 10 名学生为实验对象，进行 12 周的实验研究，其中 1 班为实验组，2 班为对照组。实验组采用下肢制动能力训练、对照组采用常规下肢训练。实验中选取 T 字跑、20 秒十字象限跳、蹬跨步制动时间、蹬跨步制动重心加速度、髋膝踝关节角度为下肢制动能力指标，其中蹬跨步相关数据和髋膝踝关节角度运用运动生物力学中运动学分析法进行分析；选取五次左右移动步法、十次四点低重心移动步法为向前移动步法指标。

实验后，得出以下结果：

（1）在下肢制动能力指标中，实验组学生各项指标均有非常显著性差异；对照组学生仅 T 字跑和制动重心加速度指标有显著性差异。

（2）在髋膝踝关节角度中，实验组学生的髋关节落地时刻角度和最大制动缓冲时刻角度有非常显著性差异，膝关节落地时刻角度有非常显著性差异，膝关节最大制动缓冲时刻角度有显著性差异，踝关节角度无显著性差异；对照组学生髋膝踝关节角度均无显著性差异。

（3）在向前移动步法指标中，实验组学生的两项指标均有非常显著性差异；对照组学生五次左右移动步法有非常显著性差异，十次四点低重心移动步法有显著性差异。

通过上述结果，得出以下结论：

（1）下肢制动能力训练在下肢制动力量、快速变向以及超等长收缩工作能力等方面的提升优于常规下肢训练。

（2）通过下肢制动能力训练后，下肢各肌肉的离心收缩能力与超等长收缩能力加强，因此蹬跨步制动时髋膝踝关节角度发生改变，使三步蹬跨步上网步法过程中的制动缓冲能力得到提升，步法技术得到改善。

（3）与常规下肢训练相比，下肢制动能力训练对向前移动步法的提升更为明显，说明下肢制动能力训练对向前移动步法的提升更有帮助。

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图 2 实验室场地情况

NOKOV 度量动作捕捉在研究中的应用摘录

3.3.4 实验器材
运动生物力学实验室使用器材： Nokov-Mars 2H 三维动作捕捉系统。整个三维捕捉系统包括：红外摄像头、转换器、电脑主机、标定杆、摄像头连接器、转换器接线、12.5mm 反光标记点、摄像头支架。三维动作捕捉系统在运动生物力学实验室进行测试。器材图与测试场地如图 1、2 所示。

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鞋帮高度对足球运动员侧切时踝关节的影响研究

关键词

足球鞋;鞋帮类型;鞋帮高度;侧切动作;踝关节;

摘要

足球鞋的鞋帮高度设计直接影响足球运动员的运动表现。本文以 30 位具有一定足球水平的男性大学生为研究对象，以试验形式分析了鞋帮高度对足球运动员侧切时踝关节的影响。结果表明，高帮鞋可以显著降低踝关节内翻角度但会降低研究对象踝关节灵活性，低帮鞋踝关节自由度最高但会增加踝关节不稳定风险，中帮鞋性能适中，没有显著的优缺点。

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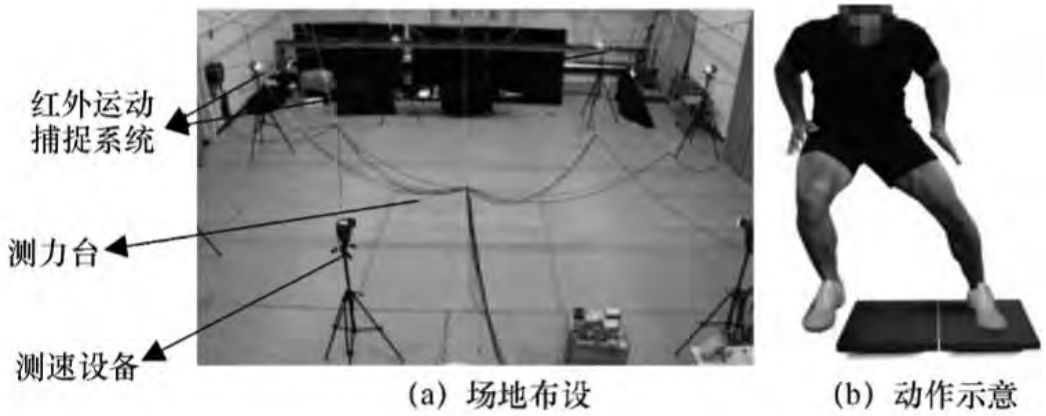

图 3　测试方法

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1.2.2 测试设备
本次测试所需设备主要包括红外运动捕捉系统测力台及计时系统等，如图 2 所示。其中，图 2(a)所示 NOKOV 三维运动捕捉系统(NOKOV，北京度量科技有限公司)主要负责对研究对象侧切运动时踝关节的活动度、角速度峰值、地面垂直反作用力峰值、踝关节力矩等参数进行捕捉;Kistler 三维测力台(Kistler，奇石乐精密机械设备)负责同步采集研究对象侧切变向触地瞬间踝关节受到来自地面的反作用力及压力中心偏移情况;测速装置(JOYI-PRO5000，北京中意明安科技有限责任公司)负责对研究对象测试过程中的奔跑速度进行捕捉。

引用格式　陶雨晴,杨帆.鞋帮高度对足球运动员侧切时踝关节的影响研究[J].中国皮革,2025,54(11):52-55.DOI:10.13536/j.cnki.issn1001-6813.2025-011-012.

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新型弹力带对摩登舞架型训练效果的运动学分析及实验研究

关键词

新型弹力带；摩登舞架型；运动学；训练效果；

摘要

摩登舞是以男女为伴的双人运动项目,竞赛中,通常是在 1'30"左右的伴奏下展示出基本舞蹈技术、流畅的舞步、双人之间的协调配合、舞蹈风格表现等。其中架型技术是舞者保持优美稳定姿态的理想轮廓,也是完成整套组合的核心技术。为了提升摩登舞者的竞争力,本研究从运动技术的形成特征出发,尝试对普通弹力带进行改良设计形成新型弹力带,运用至摩登舞教学与训练中,期望通过新型弹力带训练能够有效改善学生驼背、挺肋骨、耸肩、大臂前缩、手肘上提和下掉等问题,增强架型稳定性,达到较好的整体训练效果,优化摩登舞教学与训练方法。

本研究主要运用文献资料法、访谈法、问卷调查法、实验法、数理统计法等方法进行研究,利用三维动作捕捉仪测试和专家评分的方式对实验效果进行评价,期望为摩登舞教学与训练辅助器械的完善和创新提供一定的参考价值。研究结果为:

1、实验前通过对有基础学生和无基础学生进行摩登舞架型分析,有基础学生在 30 秒前能保持较好的架型角度,运动至 60 秒时容易出现架型变形。无基础学生在运动开始状态已经出现架型变型,并且在运动过程中架型角度呈大幅度波动,摩登舞架型的整体性是有基础学生和无基础学生面临的重要问题。

2、采用主客观相结合的评价形式对实验结果进行评价得出,新型弹力带运用到有基础学生中,能够有效改善架型"肘-肩-髋"和"肘-肩-胸骨柄"在运动中的波动幅度,能够增强脊柱的延伸性,保持架型额状面和水平面的稳定性和持久性。新型弹力带运用至无基础学生中,能够有效改善挺肋骨的问题,增强脊柱的垂直性,能够在运动前期形成较好的架型整体效果。

3、在相同训练周期中,若要达到相同的训练效果,采用新型弹力带比普通弹力带训练和徒手训练用时少。

4、通过对新型弹力带的理论分析,确立了新型弹力带是多角度的改善摩登舞架型问题。腰带设计对核心施加压力,能够改善肋骨突出问题；背带的设计能够让人体处于中立正直位,保持人体稳定的垂直轴,改善驼背问题,增强脊柱向上的延伸性；两手肘的拉力带设计能够维持大臂在水平面的稳定性,保持舞蹈架型空间；手腕至中段的拉力带设计能够训练上肢肌肉力量耐力,保证架型在额状面的稳定性。

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（2）测试仪器： Nokov-Mars 2H 三维动作捕捉系统以每秒 200 帧的数据进行采集，每人每次拍摄 180 秒， 将出现 3600 个数据进行后处理。
实验结束后，根据论文要求，选取拍摄过程中丢点最少、数据最完整的一组视频进行后处理，数据是以帧为单位。 X 轴代表前后方向，Y 轴代表左右方向， Z 轴代表垂直重心方向。采用 Motion Analysis 自带的数据采集及处理软件 Cortex 对拍摄数据进行处理和导出。 Nokov-Mars2H 三维动作捕捉系统以每秒 200 帧的数据进行采集，每人每次拍摄 180 秒，将出现 36000 个数据进行后处理。 采用 Microsoft Excel 对指标进行筛查和计算，根据论文研究需要，将提取 180 秒中的 7 个时间段数据进行分析，分别为:开始状态、30 秒、60 秒、90 秒、120 秒、 150 秒、180 秒的数据。

引用格式 蒋孟芹.新型弹力带对摩登舞架型训练效果的运动学分析及实验研究[D].广州体育学院，2020.DOI：10.27042/d.cnki.ggztc.2020.000107.

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一种击打目标可移动的拳击陪练机设计与研究

关键词

拳击陪练机；动作捕捉；结构设计；运动仿真；动作识别；

摘要

针对拳击运动传统训练方法缺乏实战体验感，陪练人员成本高、任务繁重、工作强度大等问题，本文提出了一种击打目标可移动的拳击陪练机设计思路，并完成了其机械结构设计和关键零部件选型。同时，基于运动捕捉实验，进行了击打目标的轨迹规划，将得到数据用于陪练机运动仿真分析。此外，还提出了一种拳击运动拳法识别方法。论文的工作和成果如下：

1.拳击运动员运动轨迹捕捉实验与分析。通过对四种获取运动轨迹方法的分析，确定采用光学式运动捕捉法获取运动轨迹。根据拳击陪练机模拟多种运动轨迹的要求，设计并实施了运用 Nokov 三维动作捕捉系统采集拳击运动员多种步法情形下身体移动轨迹的实验，得到了相应的的运动数据。在 Matlab 平台中绘制了身体在 X、Y、Z 方向上的位移曲线，并进行了函数拟合，得到了拳击陪练机设计的重要参数和仿真分析驱动数据。

2.拳击陪练机结构设计与分析。针对拳击运动实战特点，通过分析各种类型机械运动，确定通过三维直角坐标移动方式实现陪练机击打目标的空间运动。根据动作捕捉实验获取的设计参数，完成了关键零部件滚珠丝杠和伺服电机的设计选型，并在 solidworks 软件中完成了陪练机的三维建模。最后，选择了 Motion 运动分析法对模型进行了运动仿真及分析。经比较，模型仿真分析后得到的运动变化曲线与之前实验分析所得运动变化曲线相一致，验证了所设计模型的合理性。

3.拳击运动拳法识别研究。对拳击运动的直拳、摆拳和勾拳三种主要拳法进行了动作捕捉实验，分析了运动员在采用上述三种拳法时手部和肘部的位移、速度、加速度及肘关节角度变化的规律。通过比对，确定将肘关节角度变化极值做为拳法类别识别的特征值，并获得了三种拳法肘关节角度极值分界值。以此为基础，提出了一种通过肘关节角度变化极值判别拳击拳法的方法，为将来拳击陪练机的智能化设计提供了一种思路。

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图 2-8 实验场地

Figure 2-8 The experiment site

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借助课题组有利条件，本文实验使用的动作捕捉系统为 Nokov 光学三维动作捕捉设备，它是由北京度量科技有限公司自主研发的。该公司是一家专业光学动作捕捉设备提供商，致力于为客户提供完善的动作捕捉技术解决方案，拥有完全自主知识产权的光学动作捕捉技术，是现在国内主流动作捕捉设备提供商。 Nokov 动作捕捉设备已广泛应用于无人机、虚拟仿真、运动分析、模拟训练、人机交互等领域。

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预期状态对篮球运动员完成侧切动作时下肢运动学的影响

关键词

预期状态；篮球；侧切；下肢运动学

摘要

随着篮球运动的发展，引发的损伤也逐渐增多。同时，流行病学研究发现大学生篮球运动损伤率高达 60% 以上，其中下肢是篮球运动中最常见的损伤部位。如，ACL 损伤。因为在激烈的比赛中，运动员必须经常改变自己的运动模式，以适应新的运动环境（如，避开另一个球员或防守时被动做出动作）。在此过程中，运动员由于神经肌肉控制不良或改变未能及时调整体位策略，导致动作发生形变，进而增加膝关节负荷造成损伤的发生。因此，需了解未知状态篮球运动员完成动作时运动学特征的变化，以其通过对危险特征的分析可针对性的加强运动员在非预期状态的训练，使他们在提高运动能力的同时降低 ACL 损伤危险性。综上所述，本研究的目的是比较预期（Anticipated）和非预期（Unanticipated）状态对篮球运动员完成侧切动作时下肢运动学特征的影响，进一步探讨篮球运动员在预期和非预期状态完成侧切动作时 ACL 损伤运动学差异。了解运动状态是如何影响前交叉韧带负荷的同时将进一步了解前交叉韧带损伤机制，并有助于制定前交叉韧带损伤预防策略。研究方法：选取高水平篮球运动员和普通专选篮球大学生分别 20 名（优势腿均为右腿）。实验前测量每位受试者的步距，为了使侧切方向标准化，将胶带贴在测试区域左右各 45 度处，红外感应放置在接近速度确定点后 2 米处。受试者在测试区 5-10 米处开始进行助跑，速度达到 3.5±0.2m/s。助跑经红外感应器后数据将传输到电脑中进行随机判断后经屏幕显示出随机方向信号（左、右），需要运动员在接收到信息时立刻做出反应，身体急速侧切沿原运动方向的（左、右）前 45 度方向继续奔跑，4 步后缓冲停止奔跑。受试者从助跑到动作完成必须保证动作的连贯性，否则本次测试结果无效。同时，为防止测试过程中疲劳影响实验效果，需在实验前、中对运动员进行纵跳测试，如果纵跳距离减少 20% 为疲劳，受试者需休息几分钟继续完成实验测试。采用 Helen Hayes 反光标志点粘贴方案（29 点在受试者身上粘贴 Marker 点并运用 8 镜头 Nokov 红外光点捕捉系统分别采集受试者在预期和非预期状态完成侧切动作时下肢运动学特征数据（3 次有效数据）。通过 Cortex 软件对预期和非预期状态运动学数据进行识别处理，通过体表 Marker 建立人体多刚体模型计算得到膝关节三维角度。利用混合设计 2×2 双因素方差分析对运动学数据进行统计分析。如有交互作用，后续进行简单效应检验，不同水平用独立样本 t 检验，不同运动状态用配对样本 t 检验进行分析，所有统计分析应用 SPSS 22.0 软件完成，其中显著性标准定为一类误差概率不大于 0.05。

研究结果：通过比较预期和非预期状态对不同水平篮球运动员躯干、髋关节和膝关节的影响发现，膝关节屈曲角（F\[1.37]=6.144，P<0.05）、外展角（F\[1.20]=5.683，P<0.05）均存在显著交互作用。在预期状态，普通专选篮球大学生较高水平篮球运动员均表现出较小的膝关节屈曲角

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（P<0.05）和较大的外展角（P<0.05）；在非预期状态，普通专选篮球大学生较高水平篮球运动员表现出更小的膝关节屈曲角、更大的膝关节外展角；与预期状态相比，不论运动水平在非预期状态完成侧切动作时均表现出较大的髋关节外旋角（P<0.05）及较小的髋关节屈曲角（P<0.05）。与高水平篮球运动员比，不论运动状态，普通专选篮球大学生完成侧切动作时均表现出较小的躯干前倾角（P<0.05）以及更倾向于足跟着地。

研究结论：非预期状态完成动作任务时，着地时刻，不论运动水平均表现出较小的髋、膝关节屈曲角和较大的膝关节外展角，这些参数变化可能更易造成 ACL 损伤发生。另外，普通专选篮球大学生完成侧切动作表现出小的躯干前倾角及更倾向于足跟着地等运动学参数可能比高水平篮球运动员更易增加 ACL 损伤风险。总之，运动状态可能是造成运动员 ACL 损伤的重要的危险因素之一。

NOKOV 度量动作捕捉在研究中的应用摘录

为防止测试过程中疲劳影响实验效果，需在实验前、中对运动员进行纵跳测试，如果纵跳距离减少 20%为疲劳，受试者需休息几分钟继续完成实验测试。采用 HelenHayes 反光标志点粘贴方案（29 点）在受试者身上粘贴 Marker 点并运用 8 镜头 Nokov 红外光点捕捉系统分别采集受试者在预期和非预期状态完成侧切动作时下肢运动学特征数据（3 次有效数据）。通过 Cortex 软件对预期和非预期状态运动学数据进行识别处理，通过体表 Marker 建立人体多刚体模型计算得到膝关节三维角度。利用混合设计 2×2 双因素方差分析对运动学数据进行统计分析。如有交互作用，后续进行简单效应检验，不同水平用独立样本 t 检验，不同运动状态用配对样本 t 检验进行分析，所有统计分析应用 SPSS22.0 软件完成，其中显著性标准定为一类误差概率不大于 0.05。

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预期状态对篮球专项大学生急停跳投动作下肢运动学和动力学的影响

关键词

核心动态稳定性训练；推铅球技术动作；推铅球成绩

摘要

背向滑步推铅球是技术相对较复杂的运动项目，要求运动员在投掷过程中保持重心的稳定和身体姿势的控制。核心动态稳定性训练作为体能训练的一种，能较全面的提升个体在运动中核心肌群的稳定能力和增加运动肌群的力量。本研究针对推铅球教学训练中易忽视的核心稳定性训练，探索核心动态稳定性训练对推铅球教学效果的影响，目的是验证核心动态稳定性训练对推铅球技术掌握和成绩的提高是否有促进作用。本文通过文献资料法、专家访谈法、实验法和数理统计法等研究方法。结合背向滑步推铅球项目的技术原理以及运动学规律，设计出一套核心动态稳定性训练方案，将其应用在推铅球技术教学课中，实验结束后，对实验对象推铅球成绩和动作技术进行考评并分析。同时为了更好的对教学效果进行检验，采用 Nokov-Mars2H 三维动作捕捉系统对实验对象进行运动学数据采集，对所获得的运动学数据进行对比分析。结果如下：1，专项素质与稳定性测试：实验前后实验组与对照组 30m 跑无显著性差异（$p > 0.05$），但立定跳远、原地推铅球、原地推实心球、一分钟仰卧起坐及 FMS 得分实验前后实验组提升幅度大于对照组（$p < 0.05$）。2，推铅球成绩和技评得分：实验后，实验组推铅球成绩平均值比对照组高 0.37m，差异显著（$p < 0.05$）。技术评分两组实验对象握持球和预备姿势无显著性差异（$p > 0.05$），滑步阶段、转换阶段、最后用力和维持平衡阶段得分实验组比对照组提升显著（$p < 0.05$）。3，运动学数据分析：实验验后实验组各阶段的关节角度变化更趋于理想值，重心水平速度实验组比对照组提高显著（$p < 0.05$），出手速度和出手角度更符合技术要求。出手高度两组实验对象平均值无差异（$p > 0.05$）。通过分析得出以下结论：1，通过核心动态稳定性训练，可以促进学生专项素质提升，能有效提升核心力量，提高推铅球出手力量，加快动作速度，保证动作技术的连贯性。2，核心动态稳定性训练对推铅球成绩提高有较好帮助，试验后实验组学生铅球平均成绩更优。3，在滑步阶段，实验组学生重心水平速度较快，左腿摆动较积极，重心起伏程度较低，滑步时间较短，滑步距离较大。整个滑步技术更符合教学要求。4，在过渡阶段，对照组学生左腿下落较慢，建立起稳定的双支撑平面效果较差，对照组学生右髋上抬幅度值较大，左侧支撑技术不理想，右腿下落时右踝角度较大，没有在右腿落地时迅速的内扣及蹬伸，导致过渡阶段的水平速度损失较大。5，在最后用力阶段，实验组学生铅球速度与重心速度差值小于对照组，“人-球”整体效果更好，实验组学生出手速度和出手角度更符合教学技术要求，各项指标更趋于理想效果。

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图 2.3.3-2a 静态标定—正面　　图 2.3.3-2b 静态标定—反面

图 2.3.3-2　静态标定

Figure2.3.3-2　The subjects taken static

NOKOV 度量动作捕捉在研究中的应用摘录

使用 12 镜头红外光点运动捕捉系统（ Nokov，中国）以 200Hz 的采集频率获取 29 个粘贴在受试者身上的红外反光标志点的运动学数据，每个受试者每个动作均采集 3 次有效数据。实验地点为太原理工大学体育学院运动生物力学实验室。测试开始前需要对受试者进行静态标定（图 2.3.3-2）。静态标定的动作要求：受试者进入标定区域，双脚前后开立，略比肩宽，两臂侧平举，面向镜头，保持 5 秒。静态标定的标准：与拍摄系统相连接的电脑上的十二个显示框中均无杂点出现时即为静态标定完成。

引用格式 侯捷. 预期状态对篮球专项大学生急停跳投动作下肢运动学和动力学的影响[D].太原理工大学,2021.DOI:10.27352/d.cnki.gylgu.2021.000789.

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运动竞赛跑鞋纵向抗弯强度对人体下肢生物力学的影响研究

关键词

短跑竞技;钉鞋;抗弯强度;下肢生物力学;

摘要

专业跑鞋是运动竞赛人员的必备装备之一。本文邀请了 20 位具有一定短跑水平的男性大学生为研究对象，以 3 种不同纵向抗弯强度的钉鞋为运动竞赛跑鞋，分析了跑鞋纵向抗弯强度对人体下肢的生物力学影响。结果表明，在短跑这一竞技形态下，研究对象穿着高抗弯强度鞋时髋关节、膝关节的活动度最小；穿着中抗弯强度鞋时着地前重心平均速度水平最高，综合来看中抗弯强度鞋的性能最好。

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图 4　测试环境

NOKOV 度量动作捕捉在研究中的应用摘录

1.3 试验仪器
本次测试所需仪器主要包括测试钉鞋纵向抗弯强度的运动鞋勾心纵向抗弯刚度测试仪(CS-6045 东莞市诚胜机械设备有限公司)，测试研究对象在短跑竞技过程中的髋关节、膝关节活动度等所需的人体动作捕捉设备(NOKOV 3DMA，北京度量科技有限公司)，测试研究对象在足部着地前的重心平均速度的精密测速仪器(智能 Windows 系列，北京宏康达体育科技发展有限公司)，如图 2 所示。

引用格式 张伟,李欣.运动竞赛跑鞋纵向抗弯强度对人体下肢生物力学的影响研究[J].中国皮革,2025,54(11):85-89.DOI:10.13536/j.cnki.issn1001-6813.2025-011-019.

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运动疲劳及足部姿势对排球专项男大学生单脚落地生物力学特征的影响

关键词

排球专项疲劳测试；足部姿势；单脚落地；运动学；动力学

摘要

研究目的：排球是一项节奏快、竞争激烈、训练强度大的间歇性运动项目。着地时足部是下肢运动链的起始部分，足部姿势可能会影响踝关节到膝关节的力传递。排球运动中包含大量连续性起跳落地动作，大强度、重复性运动易引发疲劳，而运动疲劳产生的神经肌肉功能下降是诱发排球运动员下肢前交叉韧带损伤的主要原因之一。因此，本文通过排球专项疲劳测试方案模拟实际比赛情形，探究排球专项大学生在疲劳前后，不同足部着地姿势单脚落地时躯干及下肢运动生物力学的变化特征，以揭示疲劳与足部姿势对排球运动员单脚落地时前交叉韧带损伤的可能机制，为排球运动员训练和损伤预防提供理论参考。

研究方法：本研究募集了 20 名男性排球专项大学生为受试者，对其进行排球专项疲劳诱导，分别采用红外光点三维运动捕捉系统（Nokov）和测力台（Betec）同步采集，获得疲劳前后完成单脚落地时的运动学和动力学数据。运用 Cortex-642.6.2.1169 软件对运动学数据进行处理，通过逆向动力学方法计算获得关节三维力矩，关节力矩标准化为身高与体重乘积的倍数。通过 2×3 重复测量双因素方差分析（ANOVA）确定疲劳和不同足部着地姿势对运动生物力学特征的影响，后续检验通过配对样本 t 检验确定疲劳前后的差异，采用单因素方差分析确定不同足部姿势间的差异，并计算效应量。

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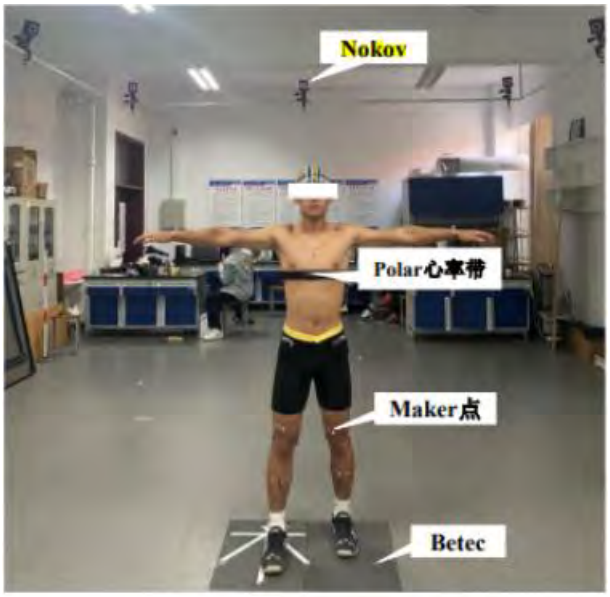

图 2.2.2-3 静态标定

Figure 2.2.2-3 The subjects taken static

NOKOV 度量动作捕捉在研究中的应用摘录

使用 12 镜头红外光点运动捕捉系统（Nokov，中国）以 100Hz 采集频率记录 29 个反光标记的位置，并与两台 Betec 三维测力台以 1000Hz 采集频率对受试者动作过程中所受地面反作用力进行同步采集，受试者三个动作均采集 3 次有效数据。测试前每个受试者均需进行初始静态站立校准试验，动作要求：受试者进入标定区域，双脚前后开立，略比肩宽，两臂侧平举，面向镜头，保持 5 秒。静态标定的标准：与拍摄系统相连接的电脑上的十二个显示框中均无杂点出现时即为静态标定完成。

引用格式 刘瑞瑞.运动疲劳及足部姿势对排球专项男大学生单脚落地生物力学特征的影响[D].太原理工大学，2021.DOI：10.27352/d.cnki.gylgu.2021.001365.

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https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C475KOm_zrgu4lQARvep2SAkueNJRSNVX-zc5TVHKmDNkjFu2FmM5TAQX4jhI22sK3ENPzSlQ4oJxYyKlvY1Kh7Y&uniplatform=NZKPT

运动前后运动鞋对人体下肢落地冲击影响差异研究

关键词

高强度运动；运动鞋；人体下肢；冲击力

摘要

运动鞋是保证人体下肢运动落地过程中得到充分缓冲的重要装备。本文通过比较 20 位篮球专项运动员在高强度运动前后的落地冲击力、负载率参数，得到运动前后运动鞋对人体下肢落地冲击的影响差异。结果表明，高强度运动后人体下肢神经肌肉控制策略会略有下降，运动鞋对人体下肢落地时的冲击力减缓效果更为明显。

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NOKOV 度量动作捕捉在研究中的应用摘录

本次试验所需数据包括研究对象在高强度运动前后从高处自然落地时所受的地面反作用力数据、足负载率、运动学特征数据等。所需设备主要包括……光学三维动作捕捉系统（NOKOV 度量，北京度量科技有限公司）等。

引用格式 贺奇乐.运动前后运动鞋对人体下肢落地冲击影响差异研究[J].中国皮革，2023,52（12）：87-91.DOI：10.13536/j.cnki.issn1001-6813.2023-012-019.

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运动拖鞋对疲劳前后步行时下肢运动学特征的影响

关键词

运动拖鞋；疲劳；步行；运动学

摘要

为了揭示运动拖鞋对疲劳前后步行时下肢运动学的影响以便科学地将运动拖鞋应用于疲劳恢复和休闲穿着等方面提供参考，募集了 15 名受试者，采用三维红外光点运动捕捉系统和三维测力平台同步采集运动学和动力学数据，通过重复测量的双因素方差分析确定运动拖鞋和疲劳对下肢关节运动学的影响.结果表明：穿着运动拖鞋步行时的下肢运动学特征主要体现在较小的髋关节活动范围、较大的踝背屈角度峰值、较大的踝跖屈角度峰值、较大的踝背屈角速度峰值等参数上.由此可得如下结论：运动拖鞋能影响步行时的部分运动学参数，同时提高下肢整体的做功能力，与疲劳因素造成的影响相反，提示这些运动学变化可能带来了更为优化的动作，对疲劳恢复起到一定的促进作用。

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NOKOV 度量动作捕捉在研究中的应用摘录

该研究的数据采集主要为髋、膝、踝关节角度和角速度,由 NOKOV 度量动作捕捉系统进行采集,所有数据均以平均值+标准差表示,采用重复测量双因素方差分析(疲劳 x 运动拖鞋)研究运动学及动力学参数,对于存在交互作用的结果,进行简单效应检验,使用 SPSS 27.0 统计软件对数据进行整理及统计.

引用格式 华立君,何金涛.运动拖鞋对疲劳前后步行时下肢运动学特征的影响[J].哈尔滨师范大学自然科学学报,2024,40(03):87-94.

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运动鞋纵向抗弯刚度对慢跑运动员下肢生物力学影响研究

关键词

慢跑运动鞋；纵向抗弯刚度；人体下肢生物力学特征；影响规律

摘要

本文选择 20 位具有一定慢跑水平的中长跑运动员作为研究对象，选择低刚度、中刚度、高刚度 3 种不同纵 向抗弯刚度的运动鞋进行慢跑状态运动员下肢生物力学特征的综合测试。结果表明：穿着不同刚度运动鞋时研究对象关 节矢状面活动度、关节矢状面关节力矩存在明显差别，相对而言高刚度运动鞋更能对人体关节形成约束，也更有益于研 究对象运动水平的提升。

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人体慢跑状态下的下肢生物力学参数主要包括髋关节、膝关节、踝关节等部位的关节角度、力矩等。本文借助 NOKOV 运动分析系统(Mars12H，北京度量科技有限公司)对研究对象慢跑状态下的生物力学参数进行捕捉;借助耀龙智能田径运动计时系统(广东耀龙智能科技有限公司)对研究对象的奔跑速度进行控制;借助 Bertec 测力台(FP4060-07-1000，美国 BERTEC 公司)对研究对象慢跑支撑期内的力、力矩、扭矩等数据进行获取。

引用格式 聂晓东.运动鞋纵向抗弯刚度对慢跑运动员下肢生物力学影响研究[J].鞋类工艺与设计,2024,4(24):12-14.

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运动性疲劳对足球运动员运动学特征的影响

关键词

运动性疲劳;前交叉韧带损伤;

摘要

研究目的:神经肌肉疲劳被认为是非接触性前交叉韧带损伤的一个危险因素,疲劳会导致运动员侧切或垂直着地时身体运动学特征发生改变,但不同专项性疲劳对足球运动员身体运动学特征的影响还不清楚。本研究的目的是对比足球专项体能测试（SAFT90）和 Yo-Yo 间歇耐力水平 2 测试（Yo-Yo IE2）对足球运动员着地时刻躯干和下肢运动学的影响,研究结果有助于更清晰地明确足球运动员不同运动性疲劳后的神经肌肉控制特征,为制定足球运动员预防前交叉韧带损伤方案提供依据,并为后继相关研究选择疲劳诱导模型提供依据。

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NOKOV 度量动作捕捉在研究中的应用摘录

研究目的：神经肌肉疲劳被认为是非接触性前交叉韧带损伤的一个危险因素，疲劳会导致运动员侧切或垂直着地时身体运动学特征发生改变，但不同专项性疲劳对足球运动员身体运动学特征的影响还不清楚。本研究的目的是对比足球专项体能测试（ SAFT90）和 Yo-Yo 间歇耐力水平 2 测试（Yo-YoIE2）对足球运动员着地时刻躯干和下肢运动学的影响，研究结果有助于更清晰地明确足球运动员不同运动性疲劳后的神经肌肉控制特征，为制定足球运动员预防前交叉韧带损伤方案提供依据，并为后继相关研究选择疲劳诱导模型提供依据。研究方法：本研究共选取 7 名大学生足球专项运动员为受试者，运用红外光点运动捕捉系统（ NokovMars2H，中国）获得受试者两种疲劳诱导前后的运动学数据（疲劳方案随机设计）。测试过程中受试者佩戴心率实时监测遥测仪（PolarTeam2，芬兰），用于保障实验的安全性和疲劳评价的有效性和客观性。运用 2\2 重复测量设计的双因素方差分析验证着地时刻两种动作下疲劳诱导和疲劳方案对足球运动员躯干、髋关节、膝关节三维角度、关节矢状面活动度以及足着地方式的影响。

引用格式 张美珍,郭浩,李文彦等.运动性疲劳对足球运动员运动学特征的影响[A].中国体育科学学会运动生物力学分会.第二十一届全国运动生物力学学术交流大会论文摘要汇编[C].中国体育科学学会运动生物力学分会：中国体育科学学会，2021：3.DOI：10.26914/c.cnkihy.2021.015399.

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https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C467SBiOvrai6TdxYiSzCnOEEIKB-6S51JyFOld47yB1sE8yFgVINdUsyqKIWjiSneWk-M4mmkeI01qeaQFa2zWIcrnbNTs7EvM%3d&uniplatform=NZKPT

运动性疲劳及不同足部姿势对下肢 ACL 损伤危险因素的影响

关键词

排球专项疲劳测试；足部姿势；单脚落地；运动学；动力学；

摘要

研究目的:排球是一项节奏快、竞争激烈、训练强度大的间歇性运动项目。着地时足部是下肢运动链的起始部分,足部姿势可能会影响踝关节到膝关节的力传递。排球运动中包含大量连续性起跳落地动作,大强度、重复性运动易引发疲劳,而运动疲劳产生的神经肌肉功能下降是诱发排球运动员下肢前交叉韧带损伤的主要原因之一。因此,本文通过排球专项疲劳测试方案模拟实际比赛情形,探究排球专项大学生在疲劳前后,不同足部着地姿势单脚落地时躯干及下肢运动生物力学的变化特征,以揭示疲劳与足部姿势对排球运动员单脚落地时前交叉韧带损伤的可能机制,为排球运动员训练和损伤预防提供理论参考。

研究方法:本研究募集了 20 名男性排球专项大学生为受试者,对其进行排球专项疲劳诱导,分别采用红外光点三维运动捕捉系统（Nokov）和测力台（Betec）同步采集,获得疲劳前后完成单脚落地时的运动学和动力学数据。运用 Cortex-64 解析软件对运动学数据进行识别处理,采用欧拉角的方法计算下肢各关节的三维角度。所有标志点三维坐标采用 Butterworth 低通滤波进行平滑,截断频率为 6.8Hz。着地时刻定义为非优势腿二、三跖骨中点反光标志点垂直速度为 0m/s 时。根据测力台坐标系在大地坐标系中的位置关系,将所有测力台数据转换到大地坐标系中进行分析,关节三维力矩通过逆动力学方法计算获得。关节力矩按受试者身高和体重的乘积标准化,所有的关节力矩都报告为外部力矩。所得数据采用 2×3 重复测量双因素方差分析方法来对结果进行统计学分析,如有交互作用,后续采用简单效应进行分析。运用配对样本 t 检验和单因素方差分析分别确定疲劳前、后和不同足部姿势间各运动学和动力学指标之间的差异。

研究结果:1)着地时刻,疲劳和不同足部姿势在髋关节屈曲角上存在显著性交互作用（F\[2,57]=3.477,P=0.038）。疲劳后较疲劳前在足部内倾（P < 0.001）、足部外倾（P < 0.001）和足部中立（P < 0.001）姿势下均表现出髋关节屈曲角减小。疲劳前（P=0.041,P=0.034）与疲劳后（P < 0.001,P=0.028）,足部内倾髋关节屈曲角较足部外倾和中立均减小。2)着地时刻下,不论足部着地姿势,与疲劳前相比,疲劳后表现出更小的躯干前倾角（P < 0.001）、髋关节外翻角（P < 0.001）和力矩（P=0.028）、膝关节屈曲角（P < 0.001）,更大的躯干向着陆侧倾斜角（P=0.035）、膝关节外翻角（P < 0.001）和力矩（P < 0.001）、膝关节内旋力矩（P=0.026）以及较高的相对重心高度（P < 0.001）；不论疲劳前后,与足部外倾和中立相比,足部内倾表现出更大的躯干向着陆侧倾斜角（P < 0.001,P=0.002）、髋关节内旋角（P < 0.001,P=0.035）、膝关节外翻角（P < 0.001,P=0.035）和力矩（P < 0.001,P=0.005）、膝关节内旋角（P < 0.001,P=0.025）,更小的髋关

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节外翻角（P < 0.001）、膝关节屈曲角（P=0.033,P < 0.001）。此外,足部内倾比足部中立还表现出更小的膝关节屈曲力矩（P=0.002）。

研究结论:1)不论足部姿势,着地时刻疲劳后躯干前倾角和膝关节屈曲角减小,导致落地时采取更为直立（僵硬）的姿势,可能导致 ACL 损伤风险增大。此外,不论足部姿势,疲劳后还表现出较大的膝关节外翻角和力矩,可能会进一步增大 ACL 损伤风险,这是不容忽视的。2)着地时刻,与足部中立和足部外倾相比,足部内倾对躯干和下肢生物力学有显著影响（如增加躯干向着陆侧倾斜角、膝关节外翻和胫骨内旋）,更容易造成 ACL 损伤风险增大,应避免足部姿势过度内倾。3)疲劳与足部姿势的联合作用使排球专项大学生完成单脚落地时下肢生物力学发生不利的变化,引起排球专项大学生下肢髋关节屈曲角减小,从而引起更高的 ACL 损伤风险。建议:臀大肌是控制躯干前倾和髋关节三维稳定性的主要神经肌肉,因此在训练过程中需加强髋关节伸肌（臀大肌）的力量和耐力训练,以便他们能在落地时有效地控制躯干屈曲,以更弯曲的姿态着地,有助于降低 ACL 损伤风险。采取足部内倾的姿势着地更容易增大 ACL 损伤,在今后的训练中,应避免过多的足部内倾,防止膝关节外翻和内旋。

引用格式 刘瑞瑞,李文彦,侯捷等.运动性疲劳及不同足部姿势对下肢 ACL 损伤危险因素的影响[A].中国体育科学学会.第十二届全国体育科学大会论文摘要汇编——专题报告（运动生物力学分会）[C].中国体育科学学会：中国体育科学学会，2022：2.DOI：10.26914/c.cnkihy.2022.004229.

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https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CPFD&dbname=CPFDTEMP&filename=ZGTK202203010010&uniplatform=NZKPT&v=wajHUOcseq-h_hDGIqj58e6TxI45aerEdS_SRH9upAIertNz8Ah6ByPOL168n4073sr0vQ0mNWQ%3d

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长跑运动员穿着不同定制鞋垫竞技时下肢生物力学特征研究

关键词

长跑运动；定制鞋垫；下肢生物力学特征

摘要

本文以长跑运动为例，对运动员穿着不同定制鞋垫开展长跑竞技时的下肢生物力学特征进行分析，以三维测力台、红外三维动作捕捉系统等采集了长跑运动员竞技过程中下肢运动学、动力学特征等。结果表明，在长跑初期，较软的鞋垫可以为运动员提供更大的推动力，但长期效果不显著；较硬的鞋垫可以显著提高运动员的长跑水平。

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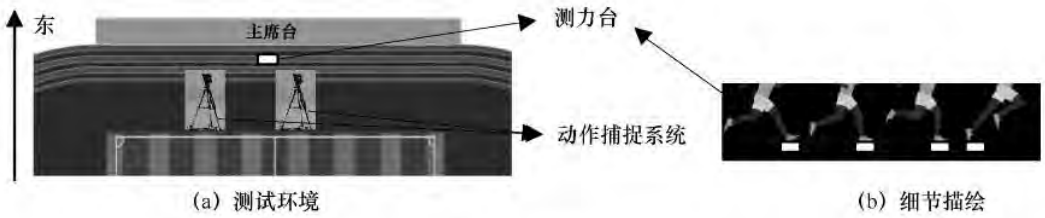

图 3 测试环境

NOKOV 度量动作捕捉在研究中的应用摘录

北京度量科技有限公司生产的ＮＯＫＯＶ红外三维动作捕捉系统主要用于对研究对象长跑测试过程中髋关节、膝关节等部位的生物力学数据进行获取。

引用格式 郭蕾.长跑运动员穿着不同定制鞋垫竞技时下肢生物力学特征研究[J].中国皮革，2024,53（08）：81-86.DOI：10.13536/j.cnki.issn1001-6813.2024-008-018.

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针刺联合经颅磁刺激治疗脑卒中后偏瘫足下垂的临床观察

关键词

针刺；经颅磁刺激；脑卒中；偏瘫；足下垂；运动功能；下肢肌力；临床观察

摘要

【目的】观察针刺联合经颅磁刺激治疗脑卒中后偏瘫足下垂的临床疗效。【方法】将 120 例患者随机分为针刺组、磁刺激组和联合组，每组各 40 例。针刺组给予针刺治疗，磁刺激组给予经颅磁刺激治疗，联合组给予针刺联合经颅磁刺激治疗，连续治疗 4 周。治疗 4 周后，评价 3 组临床疗效，观察 3 组患者治疗前后患侧腓肠肌外侧头、胫骨前肌最大积分肌电值（iEMG）的变化情况，以及下肢肌力和肌张力的情况。比较 3 组患者治疗前后步态运动参数、Fugl-Meyer 下肢运动功能（FMA）评分及 Barthel 指数（BI）评分的变化情况，并评价 3 组的安全性。【结果】（1）联合组总有效率为 95.00%(38/40)，针刺组 85.00%(34/40)，磁刺激组为 80.00%(32/40)。联合组疗效明显优于针刺组与磁刺激组，组间比较，差异有统计学意义（P<0.05）。（2）治疗后，3 组患者的背伸时胫前肌群、跖屈时腓肠肌外侧头 iEMG 值均明显改善（P<0.05），且联合组在改善背伸时胫前肌群、跖屈时腓肠肌外侧头 iEMG 值方面明显优于针刺组与磁刺激组，差异有统计学意义（P<0.05）。针刺组与磁刺激组比较，差异无统计学意义（P>0.05）。（3）治疗后，3 组患者的下肢肌力与肌张力水平均明显改善（P<0.05），且联合组在改善下肢肌力与肌张力方面明显优于针刺组与磁刺激组，差异均有统计学意义（P<0.05）。（4）治疗后，3 组患者的步态运动参数均明显改善，且联合组在改善脚最大高度、患足着地角度、步频方面明显高于针刺组与磁刺激组，在双足站立相百分比方面明显低于针刺组与磁刺激组（P<0.05）。（5）治疗后，3 组患者的 FMA 评分与 BI 评分均明显改善（P<0.05），且联合组在改善 FMA 评分与 BI 评分方面明显优于针刺组与磁刺激组，差异有统计学意义（P<0.05）。针刺组、磁刺激组比较，差异无统计学意义（P>0.05）。(6) 3 组患者的不良反应发生率比较，差异无统计学意义（P>0.05）。【结论】针刺联合经颅磁刺激治疗脑卒中后偏瘫足下垂，可明显改善患者的步态，调节患者下肢肌力和肌张力，提高患者的运动功能与日常生活能力，临床效果显著。

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NOKOV 度量动作捕捉在研究中的应用摘录

步态运动参数评估：分别于治疗前后采用 NOKOV 步态分析系统测定患者步行障碍恢复情况，记录脚最大高度、患足着地角度、步频、双足站立相百分比等步态运动学参数的变化情况。

引用格式 黄春莉，韩冰，王海涛等.针刺联合经颅磁刺激治疗脑卒中后偏瘫足下垂的临床观察[J].广州中医药大学学报，2023,40（08）：1960-1967.DOI：10.13359/j.cnki.gzxbtcm.2023.08.017.

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针刺疗法联合早期综合康复训练对脑外伤术后运动障碍患者的影响

关键词

脑外伤；运动障碍；针刺疗法；早期综合康复训练；表面肌电图；三维步态

摘要

目的 探讨针刺疗法联合早期综合康复训练对脑外伤术后运动障碍患者的影响。方法选取南阳市中心医院 2020 年 1 月至 2022 年 8 月收治的 103 例脑外伤术后运动障碍患者为研究对象，按照康复方案分为早期康复训练组(51 例)和针刺联合康复训练组(52 例)。早期康复训练组接受早期综合康复训练，针刺联合康复训练组在早期综合康复训练的基础上接受针刺疗法。康复治疗 2 个月后，对比两组临床疗效、治疗前后三维步态参数(步速、步频、左右步长差、患肢摆动相)、神经功能指标［神经元烯醇化酶(NSE)、胶质纤维酸性蛋白(GFAP)、C 反应蛋白(C R P)］、跌倒效能［修订版跌倒效能量表(MFES)］、平衡能力［Berg 平衡量表(BBS)］、日常生活能力［改良 Barthel 指数评定量表(MBI)］。结果康复治疗后，针刺联合康复训练组总有效率为 90.38%，高于早期康复训练组的 72.55%($P < 0.05$);康复治疗后，针刺联合康复训练组步速、步频、患肢摆动相高于早期康复训练组，左右步长差低于早期康复训练组($P < 0.05$);康复治疗后，针刺联合康复训练组血清 NSE、GFAP、C R P 水平低于早期康复训练组($P < 0.05$);康复治疗后，针刺联合康复训练组 MFES、BBS、MBI 评分高于早期康复训练组($P < 0.05$)。结论针刺疗法联合早期综合康复训练康复治疗脑外伤术后运动障碍患者的疗效确切，可改善三维步态、跌倒效能，提高日常生活能力，促进神经功能、运动功能恢复。

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康复治疗前后，采用 NOKOV 三维运动捕捉系统(北京度量科技有限公司)记录两组步速、步频、左右步长差、患肢摆动相。

引用格式 刘铁柱,魏艳霞.针刺疗法联合早期综合康复训练对脑外伤术后运动障碍患者的影响[J].河南医学研究,2024,33(06):1064-1067.

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针灸联合肌电生物反馈对脑卒中足下垂患者身体平衡功能、步行能力及日常生活活动能力的影响

关键词

脑卒中足下垂；针灸；肌电生物反馈；身体平衡功能；步行能力

摘要

目的：探讨针灸联合肌电生物反馈对脑卒中足下垂患者身体平衡功能、步行能力及日常生活活动能力的影响。方法：回顾性选取 2022 年 1 月到 2023 年 7 月合肥市第一人民医院神经内科和康复科收治的 100 例脑卒中足下垂患者作为研究对象，按照治疗方法分为肌电生物反馈组(47 例)和联合组(53 例，针灸联合肌电生物反馈)，比较两组痉挛程度［采用临床痉挛指数(CSI)评估］、身体平衡功能［采用 Berg 平衡量表(BBS)评估］、踝关节活动度(R OM)［主动背伸度、主动跖屈度、主动内翻度］、血液流变学指标［血浆粘度(PV)、血小板聚集率（PA R)、红细胞比容（Hct）］、步行能力［步频、步幅、患侧摆动相、患侧支持相］和日常生活活动能力［采用改良 Barthel 指数（MBI）评估］。结果：治疗后，联合组 CSI 评分低于肌电生物反馈组，BBS 评分高于肌电生物反馈组（$P < 0.05$）；治疗后，联合组主动背伸度高于肌电生物反馈组，主动跖屈度、主动内翻度低于肌电生物反馈组（$P < 0.05$）；治疗后，联合组 PV、PA R 、Hct 水平低于肌电生物反馈组（$P < 0.05$）；治疗后，联合组步频、步幅、患侧摆动相、患侧支持相水平高于肌电生物反馈组（$P < 0.05$）；治疗后，联合组 MBI 评分高于肌电生物反馈组（$P < 0.05$）。结论：针灸联合肌电生物反馈治疗脑卒中足下垂患者的效果显著，可有效改善痉挛程度、身体平衡功能、踝关节 R OM 以及血流循环，提高步行能力以及日常生活能力。

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NOKOV 度量动作捕捉在研究中的应用摘录

采用 NOKOV 三维步态分析系统检测步频、步幅、患侧摆动相、患侧支持相水平。

引用格式 马标,鲍文,程密密.针灸联合肌电生物反馈对脑卒中足下垂患者身体平衡功能、步行能力及日常生活活动能力的影响[J].四川中医,2024,42(03):184-187.

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肢体协调辅助装置结合 VR 训练对急性脑梗死颅内血管介入治疗患者步态平衡和表面肌电图的影响

关键词

肢体协调辅助装置；VR 技术；步态平衡；表面肌电图；急性脑梗死；康复训练

摘要

目的 研究肢体协调辅助装置结合虚拟现实技术（virtual reality,VR）对急性脑梗死颅内血管介入治疗患者步态平衡和表面肌电图的影响。方法 前瞻性连续纳入 2019 年 6 月—2021 年 6 月于邢台医学高等专科学校第二附属医院神经内科收治的颅内血管介入术后的急性脑梗死患者，按照随机数字表法分为对照组和观察组。对照组患者采用肢体协调辅助装置训练联合常规训练，观察组患者则采用肢体协调辅助装置训练联合 VR 训练。训练 2 个月后，采用躯干障碍量表（trunk impairment scale,TIS）、Fugl-Meyer 平衡测试评分（Fugl-Meyer balance assessment score,FMA-B）、Holden 功能性步行分级（functional ambulation classification,FAC）、改良 Barthel 量表（modified Barthel index,MBI）评估患者的躯干功能、平衡功能、步行能力和日常生活能力，记录患者的三维步态参数和表面肌电图（surface electromyography,sEMG）情况。结果 共纳入 152 例急性脑梗死患者，平均（42.64±4.17）岁，男性 81 例，女性 71 例，对照组和观察组各 76 例。训练后，观察组 TIS 量表的协调[（3.93±0.46）分 vs.(2.88±0.25)分，P<0.001]、静态坐位平衡[（5.63±1.35）分 vs.(4.99±1.04)分，P=0.004]、动态坐位平衡评分[（3.95±0.62）分 vs.(3.19±0.54),P<0.001]与 FMA-B 评分[（7.95±1.99）分 vs.(7.04±1.84 分)，P=0.010]均高于对照组，差异有统计学意义；观察组 FAC 等级高于对照组，观察组步速[（52.46±4.98）cm/s vs.(48.34±4.28)cm/s,P<0.001]、步频[（89.42±8.48）次/分钟 vs.(80.47±7.96)次/分钟，P<0.001]和患肢摆动相（38.45%±4.02%vs. 34.26%±3.87%,P<0.001）高于对照组，差异有统计学意义。观察组左右步长差[（0.62±0.06）cm vs.(0.93±0.11)cm,P<0.001]和不对称指数[（0.07±0.03）vs.(0.12±0.02),P<0.001]低于对照组，差异有统计学意义。观察组股四头肌[（0.10±0.02）cm/s vs.(0.08±0.01)cm/s,P<0.001]、胫骨前肌[（0.11±0.02）cm/s vs.(0.08±0.02)cm/s,P<0.001]和腓肠肌[（0.09±0.02）cm/s vs.(0.07±0.01)cm/s,P<0.001]的肌电图积分数值指标均高于对照组，差异有统计学意义。而观察组股四头肌[（4.38±0.37）mV vs.(5.38±0.59)mV,P<0.001]、胫骨前肌[（4.63±0.47）mV vs.(5.28±0.83)mV,P<0.001]和腓肠肌[（6.37±1.02）mV vs.(8.66±1.15)mV,P<0.001]均方根振幅均低于对照组，差异有统计学意义。观察组 MBI 评分[（67.41±7.86）分 vs.(61.57±6.63)分，P<0.001]高于对照组，差异有统计学意义。结论 急性脑梗死颅内血管介入治疗患者采用肢体协调辅助装置结合 VR 训练的方式有利于患者运动功能的恢复，可改善患者躯干功能、平衡功能和步行能力，提高其肌肉耐受力，改善日常生活质量。

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NOKOV 度量动作捕捉在研究中的应用摘录

采用 NOKOV 三维运动 捕捉系统记录两组患者的左右步长差、步频、 步速、患肢摆动相（从足趾离地到同侧足跟再 次着地的过程，占步行周期的比例）、步态不 对称指数等三维步态参数。步态不对称指数= （患肢摆动相-健肢摆动相）/（患肢摆动相+健 肢摆动相）×100%。三维步态分析时，患者在 左右大腿、小腿、足背及尾骶部安装传感器，经 姿态校准后，通过传感器捕捉步行过程中传感 器的信号轨迹，通过系统接受并转译成同步动 画，提供数据参数。患者测试前均练习 3～5 次， 所有数据均连续记录两次并取平均值。

引用格式 樊振梅,王春钚,谢婷等.肢体协调辅助装置结合 VR 训练对急性脑梗死颅内血管介入治疗患者步态平衡和表面肌电图的影响[J].中国卒中杂志,2023,18(02):194-200.

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直立抗扰时踝关节肌肉激活的力学机制研究

关键词

直立抗扰；踝关节；牵张反射；力的正反馈；肌肉反射；

摘要

研究人体内部控制机制对人机交互问题至关重要。本文以人体直立抗扰时踝关节肌肉激活的力学机制为研究课题,结合牵张反射控制和力反馈控制建立肌肉力学机理模型,设计并完成直立抗扰实验,对人体肌肉激活的力学机制展开深入研究。本文主要研究工作如下:

（1）建立直立抗扰时踝关节肌肉力学机理模型。将人体看作为绕踝关节转动的倒立摆,对人体直立平衡受力分析推导出踝关节力矩计算公式,并根据牵张反射模型和力反馈模型建立肌肉的力学机理模型。

（2）设计和搭建直立抗扰实验平台。采用从不同高度落下的沙袋作为干扰源,完成多个实验者直立抗扰实验。使用实时仿真机同步采集胫骨前肌、腓肠肌和比目鱼肌肌电数据,人体运动学数据和踝关节动力学数据。通过实验结果分析踝关节的动态特性。当人体背部受扰时,主要是比目鱼肌和腓肠肌激活调节踝关节刚度抵抗身体前倾,并且人体在前倾时踝关节刚度大于恢复时的刚度。

（3）研究基于牵张反射控制的肌肉激活。设计了基于粒子群算法的参数辨识方法,通过大量实验数据迭代寻优牵张反射控制模型参数。对比分析模型预测数据和实验数据,得到牵张反射控制模型的%VAF 大部分超过 80%,该模型能较好地预测出肌肉激活趋势。

（4）研究基于力学机制的肌肉激活。通过参数辨识得到肌肉反射控制模型参数,对比分析模型预测结果与实验数据,该模型的%VAF 大部分都超过 90%。通过分析模型预测结果可知,人体受扰时牵张反射先使肌肉激活产生肌肉力抵抗扰动,然后肌肉力的正反馈提供稳定的力补偿,调节踝关节刚度抑制人体前倾趋势。

本文设计并完成了直立抗扰实验,探究了人体直立受扰时踝关节肌肉激活的力学机制。对比分析实验数据验证了牵张反射控制模型和肌肉反射控制模型的有效性,并且分析了牵张反射和力反馈在肌肉反射中的作用,可为外骨骼和机器人的关节智能控制设计提供参考。

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图 3-4 动态捕捉系统实物图

图 3-5 Nokov 光学式动态捕捉系统示意图

NOKOV 度量动作捕捉在研究中的应用摘录

3.1.1 主要实验器材
(2) 运动学信息采集
本文采用北京度量科技有限公司生产的 Nokov 光学式动态捕捉系统来记录人体运动学信息。该动态捕捉系统属于被动式光学系统， 通过在人体关键运动部位及关节贴上标志点(Marker)记录运动信息。该 标志点表面覆盖了一层很强的反光材料，动态捕捉系统摄像头通过采集标志点的反射光线，捕捉到标志点的运动轨迹，确定每一个标志点在动态捕捉坐标系中的位置，通过其上位机软件计算出每个点在三维空间中的坐标数据。

引用格式 许先贵.直立抗扰时踝关节肌肉激活的力学机制研究[D].武汉理工大学，2020.DOI：10.27381/d.cnki.gwlgu.2020.001702.

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专项疲劳对足球运动员 ACL 损伤高危动作运动学特征的影响

关键词

足球专项体能测试；单脚落地跳；侧切；运动学

摘要

研究目的：足球比赛是高强度、长时间、多方向的间歇性运动项目。在高强度、长时间的比赛过程中，疲劳带来的神经肌肉功能下降是诱发前交叉韧带（Anterior Cruciate Ligament，ACL）损伤的一个重要的因素。因此，本文旨在探究足球专项疲劳（Soccer-specific Fatigue）对运动员完成 ACL 损伤高危动作时躯干及下肢运动学的影响。

研究方法：本研究募集了 17 名男性大学生足球运动员进行足球专项体能测试（Soccer-specific Aerobic Fitness Test，SAFT90），采用红外光点三维运动捕捉系统（Nokov）采集运动员疲劳前后完成单脚落地跳跃（35cm）和侧切动作时的运动学数据，运用 Cortex-64 5.5.0 软件对运动学数据进行识别处理。通过 2×2 重复测量双因素方差分析（ANOVA）确定疲劳前后和不同动作对躯干及下肢运动学的影响，并计算效果量。研究结果：（1）着地时刻，膝关节内收外展角在疲劳与动作间存在交互作用（F\[1,15]=5.683，p=0.031，ηp2=0.275）。侧切动作疲劳后较疲劳前表现出了较大的膝关节外展角（p=0.017，d=0.58）。（2）着地时刻，不论何种动作足球运动员疲劳后均表现出较小的躯干前倾角（p=0.043，ηp2=0.231）、髋关节屈曲角（p=0.003，ηp2=0.277）和膝关节屈曲角（p<0.001，ηp2=0.619）及较高的相对重心高度（p=0.043，ηp2=0.523）和更倾向于足跟着地（p=0.029，ηp2=0.424）。（3）着地时刻，不论疲劳侧切动作较单脚落地跳还表现出躯干前倾角小（p=0.008，ηp2=0.363）、相对重心高度低（p<0.001，ηp2=0.953）、髋关节内旋角大（p=0.037，ηp2=0.259）和倾向于足跟着地（p<0.001，ηp2=0.68）特征。（4）在膝关节屈曲角最大时刻，躯干前倾角（F\[1,14]=8.43，p=0.012，ηp2=0.376）、髋关节内旋角（F\[1,14]=6.804，p=0.021，ηp2=0.327）、膝关节外旋角（F\[1,15]=12.146，p=0.003，ηp2=0.447）在疲劳和动作间存在显著性交互作用。侧切动作疲劳后较疲劳前躯干前倾角减小（p=0.032，d=0.44）。疲劳前后侧切动作较单脚落地跳均表现出较大的髋关节内旋角（p=0.037，d=0.48 和 p=0.001，d=0.96）和较小的膝关节外旋角（p<0.001，d=0.93 和 p<0.001，d=1.77）。（5）在膝关节屈曲角最大时刻，不论疲劳与单脚落地跳相比，侧切动作表现出较小髋关节屈曲角（p=0.001，ηp2=0.556）和膝关节屈曲角（p<0.001，ηp2=0.586）。（6）干（F\[1,15]=5.281，p=0.036，ηp2=0.194）和髋关节（F\[1,15]=4.782，p=0.045，ηp2=0.242）矢状面关节活动度在疲劳和测试动作上存在显著性交互作用。疲劳后单脚落地跳躯干（p=0.031，d=0.74）和髋关节（p=0.007，d=0.44）矢状面活动度显著增大。（7）不论动作疲劳后较疲劳前表现出较大的膝关节矢状面活动度（p<0.001，ηp2=0.631）。另外，不论疲劳侧切动作较单脚落地跳还表现出

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较大的膝关节活动度（p=0.016，ηp2=0.351）。

研究结论：足球运动员疲劳后进行单脚落地跳和侧切动作时，着地时刻均表现出较小的躯干前倾角、髋关节屈曲角和膝关节屈曲角，即更为直立的落地姿势，以及足跟着地和较大的膝关节矢状面关节活动度等运动学特征，这些运动学特征变化均会增大 ACL 损伤风险。另外，侧切动作疲劳后较疲劳前还表现出较大的膝关节外展角。在膝关节屈曲角度最大时刻，疲劳前后完成不同落地动作时躯干和下肢运动学指标无显著性差异，对 ACL 损伤危险性影响不显著。足球运动员疲劳时完成 ACL 损伤高危动作时，侧切较单脚落地跳更易增加 ACL 损伤风险。建议：在今后训练中应以增大躯干前倾角等矢状面屈曲角度为主要训练目标，强调以更为弯曲的姿态着地。可对臀大肌等相关肌肉进行力量或联合收缩训练，尤其侧切动作更需有针对性训练。

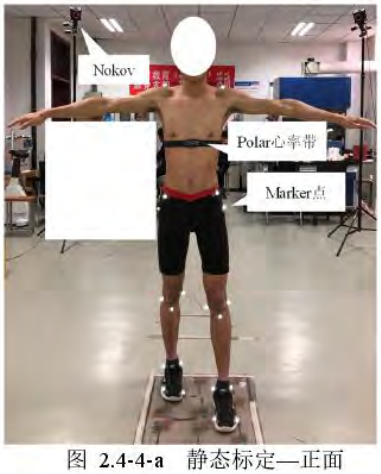

图 2.4-4-a 静态标定—正面

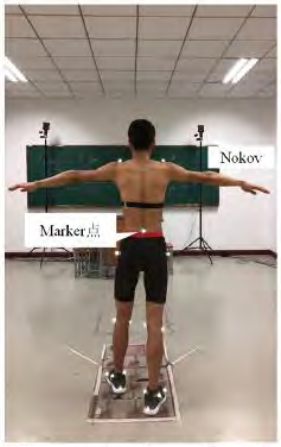

图 2.4-4-b 静态标定—反面

图 2.4-4 静态标定

Figure 2.4-4 The subjects taken static

NOKOV 度量动作捕捉在研究中的应用摘录

使用 8 镜头红外光点运动捕捉系统（ Nokov，中国）以 200Hz 的采集频率获取 23 个粘贴在受试者身上的红外反光标志点的运动学数据，每个受试者每个动作均采集 3 次有效数据。实验地点为太原理工大学体育学院生物力学实验室。测试开始前需要对受试者进行静态标定（图 2.4-4）。静态标定的动作要求：受试者进入标定区域，双脚前后开立， 略比肩宽，两臂侧平举，面向镜头，保持 5 秒。静态标定的标准：与拍摄系统相连接的电脑上的八个显示框中均无杂点出现时即为静态标定完成。

引用格式 郭浩.专项疲劳对足球运动员 ACL 损伤高危动作运动学特征的影响[D].太原理工大学，2020.DOI：10.27352/d.cnki.gylgu.2020.000909.

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https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CMFD&dbname=CMFD202201&filename=1020370753.nh&v=MTE5NDM1SHJDL0h0YkpySkViUElSOGVYMUx1eFlTN0RoMVQzcVRyV00xRnJDVVI3aWZZT1JwRnk3aFdydIBWRjI=

纵跳测试评价方法的比较研究

关键词

纵跳；纵跳带；纵跳仪；重心

摘要

目的：纵跳高度可以充分反映人体下肢爆发力，目的是比较不同纵跳测试方法的差异，为更有效准确地评价下肢爆发力提供依据。

方法：应用三种不同测试方法（重心法、纵跳带测试法、纵跳仪测试法）对 40 名（男女各 20 名）在校大学生进行摆臂纵跳和叉腰纵跳测试。采用 2×2×3 混合设计的三因素方差分析（ANOVA）检验性别、测试方法和不同纵跳方式对纵跳高度的影响。使用偏相关（PartialCorrelation）分析重心法与纵跳带测试法、重心法与纵跳仪之间的关系。应用线性回归确定纵跳带测试法、纵跳仪测试法预测重心法的纵跳高度的关系。

结果：1)三因素方差分析表明性别、动作和测试方法三者对纵跳高度没有交互作用(F\[2，76]=2.02，P=0.14)，但性别与动作(F\[1，38]=6.41，P=0.02)、动作与测试方法(F\[2，76]=24.05，P<0.001)、性别与测试方法(F\[2，76]=5.07，P=0.01)对纵跳高度均有交互作用；2)纵跳带测试法(HBelt)、纵跳仪测试法(HVJI)与重心法(HCM)均呈显著性正相关（P<0.001）；3)测试方法的准确性不受性别的影响，而与动作有关，但测试动作在纵跳带测试法和纵跳仪测试法评价纵跳高度的贡献率分别仅有 0.3%和 2.3%。

结论：与纵跳仪测试法相比，纵跳带测试法与重心法的结果误差更小，更能准确评价受试者的下肢爆发力。且女性完成叉腰纵跳时，纵跳带测试法比纵跳仪测试法的纵跳高度更精确。

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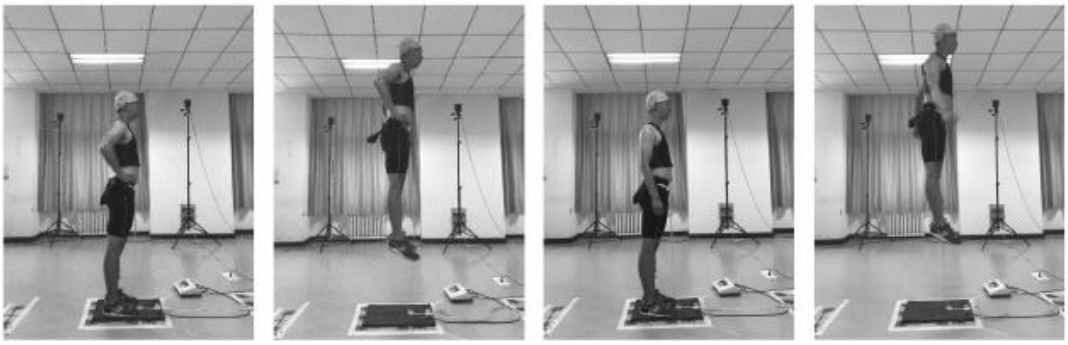

(a) 叉腰初始站立时刻　(b) 叉腰纵跳最高时刻　(c) 摆臂初始站立时刻　(d) 摆臂纵跳最高时刻

图1　两种纵跳动作下三种测试方法的测试图

Fig.1　Test diagram of three test methods during the vertical jump with and without arms

NOKOV 度量动作捕捉在研究中的应用摘录

实验前，受试者穿着实验室提供的紧身短裤及自己的运动鞋。测试前，在受试者身上贴 29 个反光标志点（头顶点，头前点，头后点，左 / 右肩峰，左 / 右肱骨外上髁，左 / 右尺骨茎突与桡骨茎突连线中点，右侧肩胛骨点，左 / 右髂前上棘，第 4、5 腰椎棘突中点，左 / 右大腿前侧，左 / 右股骨外侧髁，左 / 右股骨内侧髁，左 / 右胫骨粗隆，左 / 右腓骨外踝，左 / 右胫骨内踝，左 / 右二、三跖骨中点，左 / 右足跟）。每名受试者完成原地摆臂和叉腰纵跳动作，分别要求受试者身体直立，进行摆臂下蹲立即垂直起跳以及双手叉腰下蹲立即垂直起跳，随后双脚同时落地。起跳过程中，身体尽量保持垂直姿势（以减小躯干动作对测验成绩的影响）。每个动作各测三次，每次之间休息 1 min。通过 8 镜头红外光点运动捕捉系统（ Nokov）、纵跳带、纵跳测试仪同步采集运动学数据。应用 8 镜头红外光点运动捕捉系统 Nokov 自带数据处理软件对受试者测试动作过程中的体表标志点进行识别，后期采用 Butterworth 低通滤波进行数据平滑。使用三种方法分别对同一次纵跳的高度进行计算。

引用格式 张美珍，刘瑞瑞，郭浩等.纵跳测试评价方法的比较研究[J].河南师范大学学报（自然科学版），2021,49（01）：101-107.DOI：10.16366/j.cnki.1000-2367.2021.01.015.

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足球鞋鞋面硬度对运动员击球时足部应力的影响研究

关键词

足球鞋;鞋面硬度;击球位置;足部应力;

摘要

足球鞋的鞋面硬度可能会影响足球运动员在击球时的足部应力。本文以 18 位具有一定足球水平的业余足球运动员为研究对象，分析了几种不同鞋面硬度的足球鞋对击球时人体足部应力的影响差异。结果表明，鞋面的硬度由 40 HA 提升至 80 HA 时，击球时人体足部的应力逐渐增大，击球时的速度越高，击球点更靠近足外侧，诱发跖骨疲劳性损伤的风险越大。

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图 3　测试环境

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1.2.2 测试设备
本次测试所需设备主要包括鞋垫式足部应力分布系统、高速红外运动捕捉系统、室内人工草皮测试区等，如图 2 所示。
其中，图 2(a))所示鞋垫式足部应力分布系统(LESN STAR 3030，苏州能斯达电子科技有限公司)用于对研究对象击球时的足底应力数据进行采集;图 2(b)所示 NOKOV 三维运动捕捉系统(NOKOV，北京度量科技有限公司) 用于对研究对象击球时的动作姿态进行记录并同步压力数据;图 2(c)所示室内人工草皮测试区主要用于排除场地干扰，为研究对象击球提供稳定的测试环境。

引用格式 杨帆.足球鞋鞋面硬度对运动员击球时足部应力的影响研究[J].中国皮革,2025,54(11):90-93+100.DOI:10.13536/j.cnki.issn1001-6813.2025-011-020.

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足球运动员专项疲劳对其 ACL 损伤高危动作运动学特征的影响

关键词

前交叉韧带；足球专项体能测试；单脚落地跳；侧切；运动学

摘要

目的：探究足球专项疲劳前、后对足球运动员完成专项动作时与前交叉韧带（anterior cruciate ligament，ACL）损伤相关的躯干及下肢运动学影响。方法：17 名足球运动员进行足球专项体能测试（soccer-specific aerobic fitness test，SAFT90），采用三维红外光点运动捕捉系统采集和处理运动员疲劳前、后完成单脚落地跳和侧切动作时的运动学数据。运用 2×2 重复测量双因素方差分析（ANOVA）确定疲劳前、后和不同动作，以及疲劳后不同动作和特征时刻对运动学的影响。结果：与疲劳前相比，疲劳后运动员不论何种动作着地时刻均表现出较小的躯干前倾角（P=0.043）、髋关节屈曲角（P=0.003）和膝关节屈曲角（P < 0.001）及倾向于足跟着地（P=0.029）。疲劳后侧切动作表现出较大的膝关节外展角（P=0.017）。与单脚落地跳相比，侧切动作还表现出较小的躯干前倾角（P=0.008）以及更倾向于足跟着地（P < 0.001）。膝关节屈曲角最大时刻，疲劳后仅侧切动作躯干前倾角度减小（P=0.032）；而与单脚落地跳相比，侧切动作表现出较小髋关节屈曲角（P=0.001）和膝关节屈曲角（P < 0.001）。同时，还表现出较大的膝关节矢状面关节活动度（P < 0.001）。疲劳后膝关节屈曲角最大时，两个动作均表现出较大的髋关节内旋角（P=0.002，P=0.002）；与膝关节屈曲角最大时相比，着地时刻还表现出较小的躯干前倾角度（P=0.004）。结论：着地时刻，两种动作专项疲劳诱导后均使人体以更为直立的姿态着地，同时膝关节矢状面活动范围增大等因素均可能增大 ACL 损伤的风险。着地时刻，侧切动作表现出的运动学特征可能造成 ACL 损伤风险大于单脚落地跳。膝关节屈曲角最大时刻，侧切动作疲劳后运动学特征亦可能增加 ACL 损伤的风险。疲劳后，两个动作着地时刻可能比膝关节屈曲角最大时刻更易造成 ACL 损伤，但还需注意膝关节屈曲角最大时髋关节内旋。

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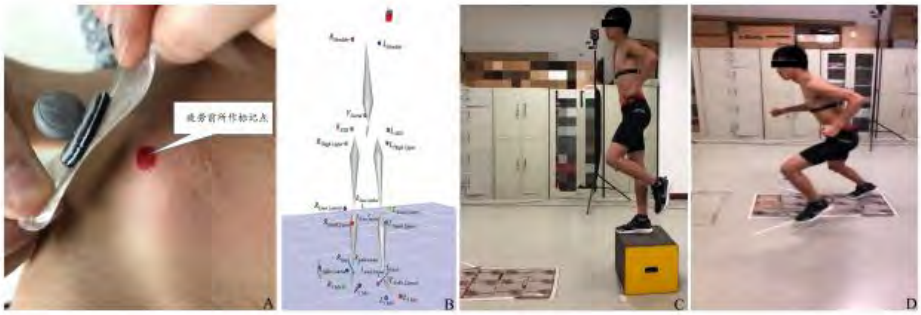

图2　受试者测试过程

Figure 2.　The Process of SAFT[90]

注:A为疲劳前反光标志球放置位标记;B为红外反光标志球黏贴方案;C为单脚落地反跳;D为侧切。

NOKOV 度量动作捕捉在研究中的应用摘录

实验前告知受试者实验方案，测试时穿着自备运动鞋和统一配备的紧身上衣和短裤。在进行充分准备活动后，由同一操作人员为其贴上反光标志点（疲劳后再次黏贴标志点时可根据疲劳前黏贴所作标记进行检查，亦减少因黏贴位置不同所造成的误差，图 2A）。采用 23 点反光标志球黏贴方案（图 2B），使用 8 镜头红外光点运动捕捉系统（Nokov，中国）以 200 Hz 的采集频率对足球运动员专项体能测试方案前、后两个专项动作-单脚落地跳（Wright et al.，2017）和侧切动作（张美珍，2012）进行运动学数据采集（图 2C、图 2D）。受试者在整个测试过程中佩戴心率遥测仪用于监测心率。SAFT90 诱导疲劳期间，实验人员记录全程心率和不同时间点（0 min、45 min、60 min 和 105 min）的主观疲劳程度。在完成 SAFT90 后即刻再次进行专项动作的运动学数据采集，每名受试者每个动作均采集 3 次有效数据。

引用格式 郭浩，刘瑞瑞，王广宇等.足球运动员专项疲劳对其 ACL 损伤高危动作运动学特征的影响[J].中国体育科技，2021,57（07）：53-61.DOI：10.16470/j.csst.2019229.

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基于注意力机制的 CNN-LSTM 下肢关节预测方法

关键词

肌电信号；动作捕捉；卷积神经网络；长短期记忆；注意力机制；

摘要

基于卷积神经网络(CNN)预测下肢关节角度中会丢失一定的人体肌电(EMG)信号特征信息，从而导致整体预测不准确。针对此问题，提出了一种基于注意力机制(AM)的长短期记忆(LSTM)网络和 CNN 模型的下肢关节角度预测方法。采集人体表面肌电信号和动作捕捉下肢关节角度，将肌肉信号映射的肌肉活跃度特征作为输入，开展了下肢关节角度预测研究。研究结果表明：下肢髋、膝、踝 3 个关节角度预测中，基于 AM 的 CNN-LSTM 模型比 CNN-LSTM 模型和 CNN 模型得到的平均绝对误差(MAE)值平均降低了 26.4%和 53%,均方根误差(RMSE)值平均降低了 32.3%和 50.9%。验证了该模型在下肢关节角度预测中有更高的准确率。

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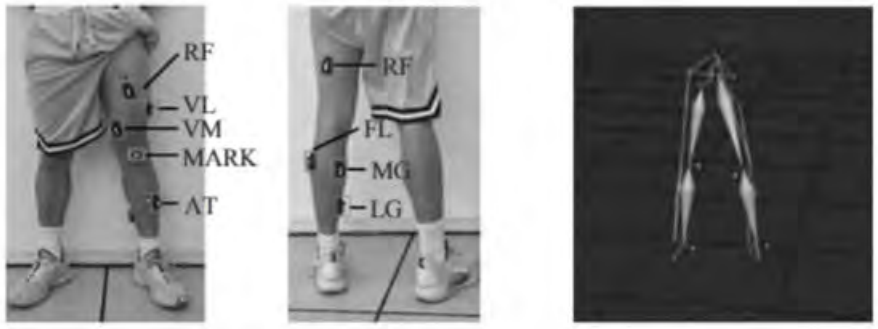

(a) 贴点位置　　(b) 下肢模型

图 1　平地行走实验

Fig 1　Level walking experiment

NOKOV 度量动作捕捉在研究中的应用摘录

1 人体下肢连续行走信息采集
人体下肢连续行走是下肢外骨骼人机交互研究中的重要环节，涉及运动学和肌电信号等领域\[^1]，连续行走中重要参数体现在髋、膝、踝关节角度和肌电信号，因此对上述下肢三关节角度和肌肉信号采集进行下肢运动预测估计。
*实验设备选用 TrignoTM wireless EMG 作为表面肌电信号的采集装置，将传感器粘贴于下肢进行表面肌电信号采集。下肢角度信号采集利用 **NOKOV** 设备进行，其主要由光学动作捕捉镜头采集受试者的速度、加速度、角度等运动学数据。*

引用格式 崔冰艳,琚凯,张祥,等.基于注意力机制的 CNN-LSTM 下肢关节预测方法[J].传感器与微系统,2026,45(04):62-66.DOI:10.13873/J.1000-9787(2026)04-0062-05.

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疲劳状态下鞋底纵向刚度对篮球运动员踝关节稳定性的影响研究

关键词

疲劳状态；篮球鞋纵向刚度；篮球运动员；踝关节稳定性

摘要

本文以 20 位业余篮球爱好者为研究对象，对其在疲劳状态前后以不同落地方式进行极限跳跃时的踝关节生物力学特征参数进行获取，得到疲劳状态下鞋底纵向刚度对篮球运动员踝关节稳定性的影响规律。结果表明：在疲劳状态前，研究对象穿着不同纵向刚度篮球鞋极限跳跃落地时踝关节稳定性差异不大；在疲劳状态后，研究对象穿着高纵向刚度篮球鞋极限跳跃落地时踝关节内翻角度更小，垂直方向受到的冲击力更小，踝关节稳定性更强。

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图 1　试验设备

NOKOV 度量动作捕捉在研究中的应用摘录

1.1.2 试验设备
*根据贺奇乐的研究显示，可以直观反映人体踝关节稳定性的指标主要包括踝关节内翻角、活动度等运动学指标，以及垂直方向地面反作用力和活动力矩等动力学指标。获取这些指标所需设备主要包括运动捕捉设备（**NOKOV，北京度量科技有限公司**）、三维测力台（Betec，上海彤宙数字技术有限公司）、电子摸高测试器（1200 mm，沧州博昇体育器材有限公司）等。图 1 为试验设备基本布置情况。*

引用格式 刘于溪.疲劳状态下鞋底纵向刚度对篮球运动员踝关节稳定性的影响研究[J].中国皮革,2026,55(02):88-91+101.DOI:10.13536/j.cnki.issn1001-6813.2026-002-017.

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下视野遮挡对青年人跨越高度障碍时运动生物力学特征的影响

关键词

下视野遮挡；跨越障碍；运动生物力学；跌倒损伤预防

摘要

目的 探究下视野遮挡与障碍物高度对健康青年人跨越障碍时运动生物力学特征的独立及交互影响，以深化对视觉–动作控制机制的理解，并为视觉受限环境下预防跌倒损伤提供运动生物力学依据。方法 15 名男性健康青年人以舒适步速行走并跨越分别为腿长的 10%、20%、30%高度的障碍物，采用搬箱遮挡法模拟无遮挡、低遮挡、高遮挡的下视野遮挡程度。使用**Nokov 三维运动捕捉系统**与 Bertec 三维测力台采集运动学以及前导腿着地时刻的动力学数据。结果 无论障碍物高度，下视野遮挡均会导致前导腿着地时刻躯干后倾程度显著增大（P<0.001），躯干由无遮挡时的外旋力矩转为内旋力矩（P=0.001），最小膝外翻角（P<0.001）及额状面活动度（P=0.008）显著减小；无论下视野遮挡程度，障碍高度增加均会显著增大髋关节屈曲角峰值（P<0.001）、矢状面活动度（P<0.001）及着地时刻膝关节屈曲角（P=0.018）、髋关节伸展力矩（P=0.034）；障碍高度大于 20%腿长时，下视野遮挡导致膝屈曲角峰值（P<0.001）和矢状面活动度（P<0.001）显著增大。在 30%障碍高度下，下视野遮挡越多，前导腿着地时膝外翻角越大（P=0.004）。结论 下视野遮挡伴随躯干后倾、转向支撑腿侧及减少膝外翻等即时代偿行为。随着障碍高度增加，关节活动度与力矩显著上升，且代偿策略不足以抵消。当障碍高度达到腿长 20%时，遮挡的影响凸显，表现为膝关节屈曲增加以提供缓冲；而当高度增至腿长 30%并伴重度遮挡时，前导腿着地时刻膝外翻角显著增大，预示着损伤风险上升。

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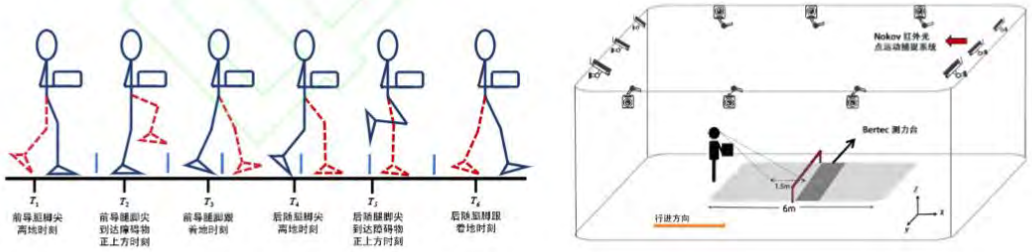

（a）步态特征时刻划分　　（b）实验环境设置

图 1 特征时刻划分及实验环境设置

Fig.1 Characteristic moment segmentation and experimental environment configuration (a) Characteristic moment segmentation, (b) Experimental environment configuration,

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> *每位受试者依次完成所有高度与遮挡条件的组合测试，每组条件采集 5 次有效数据，并最终选取 3 次同侧跨越数据用于分析。应用 12 镜头红外光点三维运动捕捉系统（采样频率 200 Hz，**Nokov Mars2H**，北京度量科技有限公司，中国）及三维测力台（采样频率 1 kHz，Betec 公司，美国）同步采集运动学和动力学数据。*

引用格式 郭晶晶,张优佳,尹超,等.下视野遮挡对青年人跨越高度障碍时运动生物力学特征的影响[J/OL].医用生物力学,1-13.https://link.cnki.net/urlid/31.1624.R.20260323.0943.002.

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https://kns.cnki.net/kcms2/article/abstract?v=H8HwaL3t0AvTRlV_FtJzyjr3Bf9WlUUpN_oLJSJyabaebgpgymMoAPGYpwjiAzQe7-BebrdBwUCmofOoTzrO7HHDvbus_KywaQOJoTqw5b4gBLcJ7QSV-A5wGM-3QDCVIacSQSBZ-DpG5cNcvC6oRg6pG2r4ud8eC3R3Kaw5wXyzBZ78uB4s3A==&uniplatform=NZKPT&language=CHS

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渐进式康复护理在帕金森病患者中的应用效果

关键词

渐进式康复护理;帕金森病;步态功能;平衡能力;生命质量;护理满意度

摘要

目的：观察渐进式康复护理在帕金森病患者中的应用效果。方法：选取 2021 年 3 月至 2024 年 2 月该院收治的 92 例帕金森病患者进行前瞻性研究，按随机数字表法将其分为对照组（n=46）、观察组（n=46）。对照组采用常规康复护理，观察组采用渐进式康复护理，比较两组护理前后步态功能指标[步速、步宽、6 min 步行试验距离（6MWD）]水平、平衡能力[Berg 平衡量表（BBS）]评分、生命质量[帕金森病病生活质量问卷（PDQ-39）]评分，以及护理满意度。结果：护理后，两组步速、步宽均大于护理前，且观察组大于对照组，两组 6MWD 均长于护理前，且观察组长于对照组，差异有统计学意义（P<0.05）；护理后，两组 BBS 评分均高于护理前，且观察组高于对照组，差异有统计学意义（P<0.05）；护理后，两组躯体活动、生理不适、生活影响、精神健康、社会支持、耻辱感、沟通影响、感知等 PDQ-39 评分均低于护理前，且观察组低于对照组，差异有统计学意义（P<0.05）；观察组护理满意度为 93.48%，高于对照组的 76.09%，差异有统计学意义（P<0.05）。结论：渐进式康复护理应用于帕金森病患者可改善步态功能、生命质量，提高平衡能力评分和护理满意度的效果优于常规护理。

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1.3 观察指标（1）比较两组护理前后步态功能指标水平。采用 NOKOV 度量动作捕捉系统采集步速、步宽、6 min 步行试验距离（6MWD）。（2）比较两组护理前后平衡能力评分。采用 Berg 平衡量表（BBS）评估，总分 0~56 分，分值越高，平衡能力越好。（3）比较两组护理前后生命质量评分。采用帕金森病生活质量问卷（PDQ-39）评估，包括躯体活动（10 个条目）、生理不适（3 个条目）、生活影响（6 个条目）、精神健康（6 个条目）、社会支持（3 个条目）、耻辱感（4 个条目）、沟通影响（3 个条目）、感知（4 个条目）等 8 个维度，每个条目 0~4 分，总分 0~156 分，评分与生命质量呈负相关。（4）比较两组护理满意度。采用纽卡斯尔护理满意度量表评估，总分 95 分，其中 <38 分为非常不满意，38~56 分为不满意，57~75 分为一般满意，75~94 分为满意，95 分为非常满意。满意度 =（非常满意 + 满意）例数 / 总例数 × 100%。

引用格式 王晓丹,周红,刘青.渐进式康复护理在帕金森病患者中的应用效果[J].中国民康医学,2026,38(9):160-163.

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https://kns.cnki.net/kcms2/article/abstract?v=7jvqSXIa2LVgJNY1pmmatoz35KoEQdbyhaeAjidCSMbVfbfpqnWCdj6NhkqC-Q6hJpfiDLXLEb-06S7kSARpa9cGoP3cg3SRG3_GBEftWOnmEsGxgLRds-iRWKrR82bj0LVnrWrpyC1kj89Mng-X6YDTHvWBNb7n&uniplatform=NZKPT

肌电触发式神经肌肉电刺激联合经皮耳迷走神经电刺激对脑梗死后偏瘫的影响

关键词

肌电触发式神经肌肉电刺激;经皮耳迷走神经电刺激;脑梗死;偏瘫;肢体运动功能;

摘要

目的:探讨脑梗死后偏瘫患者应用肌电触发式神经肌肉电刺激(EMG-NMES)联合经皮耳迷走神经电刺激(TAVNS)的效果。方法:选取 2022 年 9 月—2024 年 8 月我院收治的 108 例脑梗死后偏瘫患者为研究对象,以随机数字表法分为两组。两组均给予常规康复训练,对照组 54 例给予 TAVNS,观察组 54 例在对照组基础上增加 EMG-NMES。对比两组患者肢体运动功能、步态时间运动学参数、步态空间运动学参数及表面肌电值。结果:干预后,观察组 FuglMeyer 运动功能评分量表(FMA)中上肢、下肢分值均高于对照组(P<0.05);干预后,观察组患侧支撑时间长于对照组,步态周期、双足支撑时间均短于对照组(P<0.05);干预后,观察组步频、步速、步长、步幅均高于对照组(P<0.05);干预后,观察组肱二头肌、胫骨前肌、腓肠肌的表面肌电值均高于对照组(P<0.05)。结论:EMG-NMES 联合 TAVNS 应用,能够有效提高脑梗死后偏瘫患者肢体运动功能,改善步态参数异常情况及相关肌群肌电活动水平。

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1.3 观察指标 （1）肢体运动功能：干预前、干预 6 周后，采用 Fugl-Meyer 运动功能评分量表（FMA）评估患者肢体运动功能，FMA 分为上肢运动、下肢运动 2 个部分，分值分别为 0~66 分、0~34 分，得分越高提示患者肢体运动功能越好。 （2）步态时间运动学参数：干预前、干预 6 周后，采用三维动作捕捉系统（北京度星科技有限公司，型号：NOKOV）检测患者患侧支撑时间、步态周期、双足支撑时间。 （3）步态空间运动学参数：干预前、干预 6 周后，采用三维动作捕捉系统检测患者步频、步速、步长、步幅。 （4）表面肌电值：干预前、干预 6 周后，采用高级神经网络重建仪检测患者肱二头肌、胫骨前肌、腓肠肌表面肌电值。

引用格式 孙梦君,康春风,彭难难.肌电触发式神经肌肉电刺激联合经皮耳迷走神经电刺激对脑梗死后偏瘫的影响[J].医学理论与实践,2026,39(12):2122-2125.DOI:10.19381/j.issn.1001-7585.2026.12.040.

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Part III VR/AR

In vivo Pedestrian Behaviour upon Motor Vehicle Conflicts: Experimental Framework and Initial Results

Abstract

Pedestrians remains a significant portion, i.e., 26%, of all road traffic deaths given their extreme vulnerability in motor vehicle collisions (MVCs) \[1]. The instinctive reactions of pedestrians upon traffic conflicts largely determine the occurrence and severity of accidents \[2-3]. Yet, the absence of human-like behaviour in existing research surrogates, e.g., crash dummies, human body models, has limited their potential and application in advanced vehicle safety systems on roads. Up to now, no systematic investigation on such in vivo behaviour is available from existing epidemiological, computational, or dummy-based experimental studies \[4-5]. This study proposes an experimental framework for extracting typical vivo pedestrian behaviour in motor vehicle conflicts. When the volunteers, i.e., pedestrians, entered near-real immersive virtual reality (VR) traffic scenarios. A well-controlled dangerous traffic scene was generated as a visual stimulus to pedestrians. Real-time biomechanical signals of the subjects were recorded during the subsequent natural reactions.

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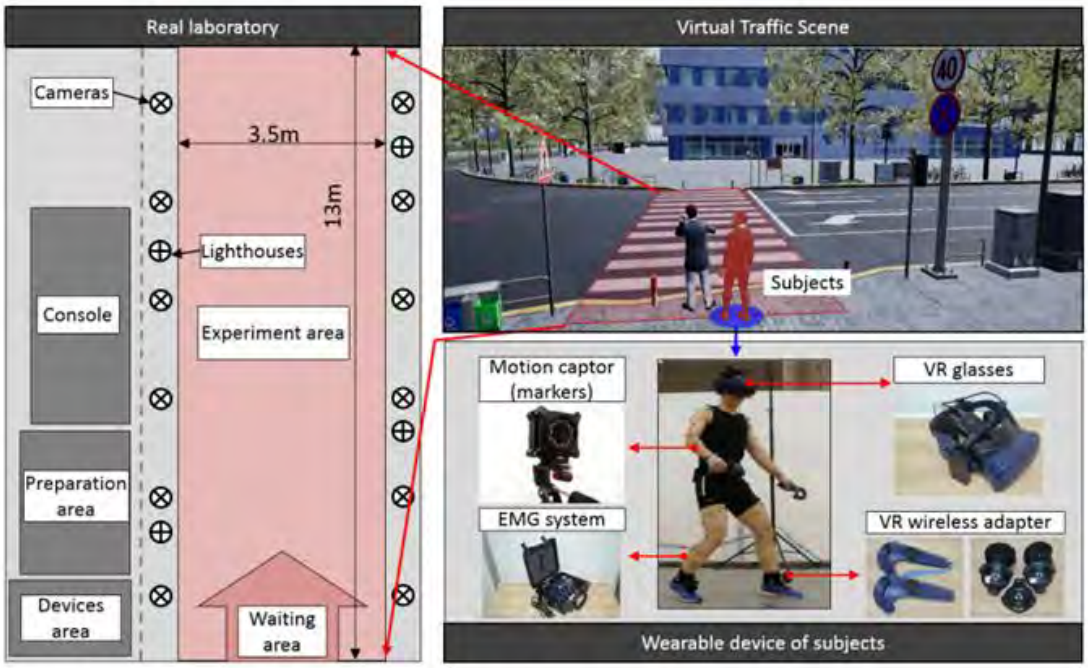

Fig. 1. The overall experiment design

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Module II: Kinetic capture system. Recording the motion information of subjects during the experiment (No. Mars 2H; Beijing Nokov Science & Technology Co., Ltd). This system consists of 12 motion capture cameras (100 Hz), 54 markers and the relevant software module. 12 cameras were fixed on the edge of the subjects' movement range by tripods (Fig. 1.). Fifty-four markers were attached to the surface of subjects' body through double-sidedtape \[6].

Citation Li Q, Zhou Q, Chen W, et al. In Vivo Pedestrian Behaviour upon Motor Vehicle Conflicts: Experimental Framework and Initial Results[C]//Proceedings of IRCOBI Asia Conference. 2021: 1-2.

Link
https://www.researchgate.net/publication/343306944_In_vivo_Pedestrian_Behaviour_upon_Motor_Vehicle_Conflicts_Experimental_Framework_and_Initial_Results

Kinetic and Kinematic Features of Pedestrian Avoidance Behavior in Motor Vehicle Conflicts

Keywords

Pedestrian safety; Active behavior; Kinematics; Biomechanics; Integrated safety; Volunteer testing

Abstract

The active behaviors of pedestrians, such as avoidance motions, affect the resultant injury risk in vehicle–pedestrian collisions. However, the biomechanical features of these behaviors remain unquantified, leading to a gap in the development of biofidelic research tools and tailored protection for pedestrians in real-world traffic scenarios. In this study, we prompted subjects ("pedestrians") to exhibit natural avoidance behaviors in well-controlled near-real traffic conflict scenarios using a previously developed virtual reality (VR)-based experimental platform. We quantified the pedestrian–vehicle interaction processes in the pre-crash phase and extracted the pedestrian postures immediately before collision with the vehicle; these were termed the "pre-crash postures." We recorded the kinetic and kinematic features of the pedestrian avoidance responses — including the relative locations of the vehicle and pedestrian, pedestrian movement velocity and acceleration, pedestrian posture parameters (joint positions and angles), and pedestrian muscle activation levels—using a motion capture system and physiological signal system. The velocities in the avoidance behaviors were significantly different from those in a normal gait ($p < 0.01$). Based on the extracted natural reaction features of the pedestrians, this study provides data to support the analysis of pedestrian injury risk, development of biofidelic human body models (HBM), and design of advanced on-vehicle active safety systems.

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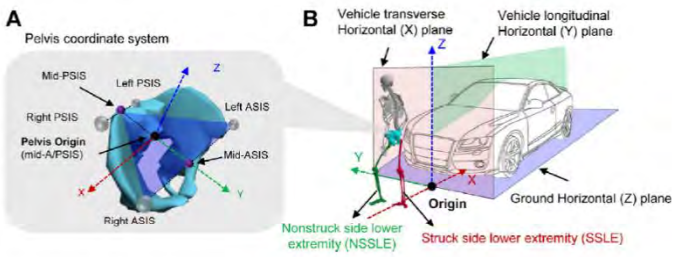

FIGURE 1 | Illustration of the locations of the coordinate system; **(A)** pedestrian local coordinate system, **(B)** vehicle coordinate system.

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The pedestrian kinetic and kinematic features include the relative locations of the vehicle and pedestrian, the pedestrian's movement velocity and acceleration, their posture (joint positions and angles), and their muscle activation levels. The data were recorded and extracted using the 12 cameras (100 Hz) of the motion capture system (No. Mars 2H; Beijing Nokov Science and Technology Co., Ltd.) by tracking 54 markers. In addition, 11 joints were used to describe the pedestrian posture (Arnold et al., 2010) (Supplementary Figure S1). The pedestrian kinematics were inversed using OpenSim and the "Full Body Model" (Rajagopal et al., 2016).

Citation Li Q, Shang S, Pei X, et al. Kinetic and kinematic features of pedestrian avoidance behavior in motor vehicle conflicts[J]. Frontiers in bioengineering and biotechnology, 2021, 9: 783003.

Link https://www.frontiersin.org/articles/10.3389/fbioe.2021.783003/full

Leveraging Motion Capture System for High Accuracy AR-Assisted Assembly

Keywords

Augmented Reality · Pose tracking · AR-assisted assembly · Motion capture system · Freeform steel structure

Abstract

Augmented Reality (AR) allows workers to construct buildings accurately and intuitively without the need for traditional tools like 2-D drawings and rulers. However, accurately tracking worker's pose remains a significant challenge in existing experiments due to their continuous and irregular movement. This research discusses a series of methods using cameras and algorithms to achieve the 6-DoF pose tracking function and reveal the relationship between each method and corresponding tracking accuracy in order to figure out a robust approach of AR-assisted assembly. This paper begins with a consideration of the possible limitations of existing methods including the image drift associated with visual SLAM and the time-consuming nature of fiducial markers. Next, the entire hardware and software framework was introduced, which elaborates on how the motion capture system is integrated into the AR-assisted assembly system. Then, some experiments have been carried out to demonstrate the connection between the system set up and pose tracking accuracy. This research shows the possibility to easily finish assembly task based on AR technology by integrating motion capture system.

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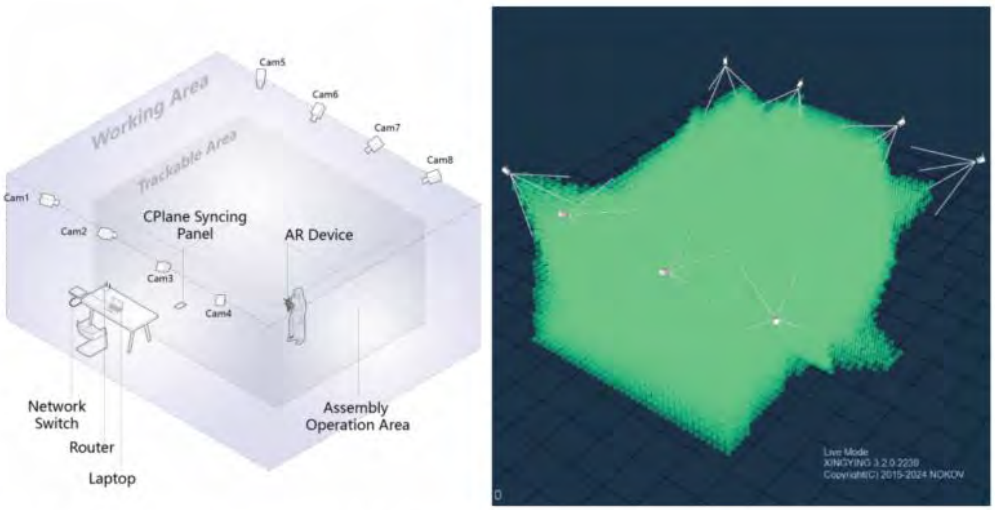

Fig. 1. AR-assisted assembly site setup (Left) and 6-DoF pose tracking area (Right)

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3 Methods
The following experiments were conducted in an 8.0 \ 7.6m site (Fig. 1), using 6-DoF motion capture system provided by NOKOV and a custom-designed AR device. The 6-DoF motion capture system comprises 8 high-speed infrared optical lenses, each equipped with numerous infrared LED lights mounted on their panels. These lights illuminate highly reflective markers, which then reflect light back to the lenses, enabling the calculation of the 2D coordinates of each marker. Finally, by integrating data from multiple lenses capturing different perspectives, the system computes the 3D coordinates of each highly reflective marker.

Citation Liu H, Xie X, Li Y, et al. Leveraging Motion Capture System for High Accuracy AR-Assisted Assembly[C]//The International Conference on Computational Design and Robotic Fabrication. Singapore: Springer Nature Singapore, 2024: 77-90.

Link
https://ev.publinks.top/app/doc/?docid=cpx_M285019cf199c8660514M7e2c1017816521&pageSize=100&index=1&searchId=8f9b21a796bf4645926895d3962b7102&resultsCount=4&usageZone=resultslist&usageOrigin=searchresults&searchType=Quick

Redirected Smooth Mappings for Multi-user Real Walking in VR

Keywords

Virtual reality; Multi-user real walking; Multi-user physical interaction; Redirected smoothing mapping; Automatic collision avoidance

Abstract

We propose a novel technique to provide multiuser real walking experiences with physical interactions in virtual reality (VR) applications. In our system, multiple users walk freely while navigating a large virtual environment within a smaller physical workspace. These users can interact with other real users or physical props in the same physical locations. The key of our method is a redirected smooth mapping that incorporates the redirected walking technique to warp the input virtual scene with small bends and low distance distortion. Users possess a wide field of view to explore the mapped virtual environment while being redirected in the real workspace. To keep multiple users away from the overlaps of the mapped virtual scenes, we present an automatic collision avoidance technique based on dynamic virtual avatars. These avatars naturally appear, move, and disappear, producing as little influence as possible on users' walking experiences. We evaluate our multiuser real walking system through formative user studies, and demonstrate the capability and practicability of our technique in two multiuser applications.

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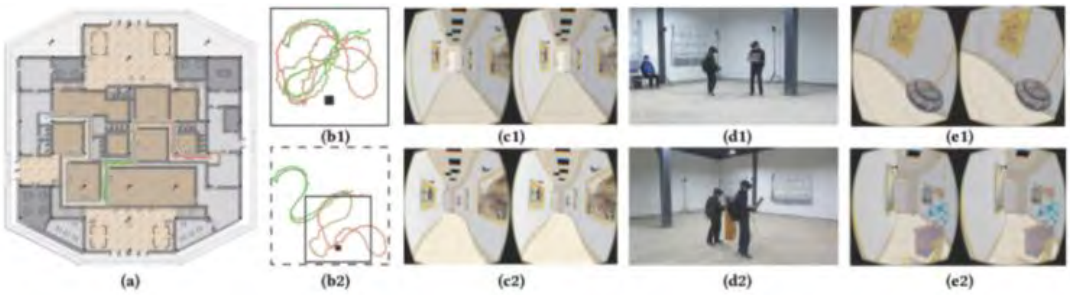
(a1) Coming close **(b1)** Walking together **(c1)** Going apart



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Tracking System. As shown in Figures 1 and 8, our multiuser real walking and interaction experiments run in a 10m × 10m physical room with 12 Nokov motion capture cameras (http://www. nokov.com/). An iron pillar (Figure 8(b)) in the room is treated as an interior obstacle (the black box in Figure 8(a)) that is avoided by f(V). Since users are redirected in f(V), they can walk freely without hitting the iron pillar. The average position of three markers, which are placed on top of a user's head, determines the user's position.

Citation Zhi-Chao Dong, Xiao-Ming Fu, Zeshi Yang, and Ligang Liu. 2019. Redirected Smooth Mappings for Multiuser Real Walking in Virtual Reality. ACM Trans. Graph. 38, 5, Article 149 (October 2019), 17 pages. https://doi.org/10.1145/3345554

Link https://dl.acm.org/doi/abs/10.1145/3345554

Safety envelope of pedestrians upon motor vehicle conflicts identified via active avoidance behaviour

Keywords

Virtual reality; Multi-user real walking; Multi-user physical interaction; Redirected smoothing mapping; Automatic collision avoidance

Abstract

Human reaction plays a key role in improved protection upon emergent traffic situations with motor vehicles. Understanding the underlying behaviour mechanisms can combine active sensing system on feature caption and passive devices on injury mitigation for automated vehicles. The study aims to identify the distance-based safety boundary ("safety envelope") of vehicle – pedestrian conflicts via pedestrian active avoidance behaviour recorded in well-controlled, immersive virtual reality-based emergent traffic scenarios. Via physiological signal measurement and kinematics reconstruction of the complete sequence, we discovered the general perception-decision-action mechanisms under given external stimulus, and the resultant certain level of natural harm-avoidance action. Using vision as the main information source, 70% pedestrians managed to avoid the collision by adapting walking speeds and directions, consuming overall less "decision" time (0.17–0.24 s vs. 0.41 s) than the collision cases, after that, pedestrians need enough "execution" time (1.52–1.84 s) to take avoidance action. Safety envelopes were generated by combining the simultaneous interactions between the pedestrian and the vehicle. The present investigation on emergent reaction dynamics clears a way for realistic modelling of biomechanical behaviour, and preliminarily demonstrates the feasibility of incorporating in vivo pedestrian behaviour into engineering design which can facilitate improved, interactive on-board devices towards global optimal safety.

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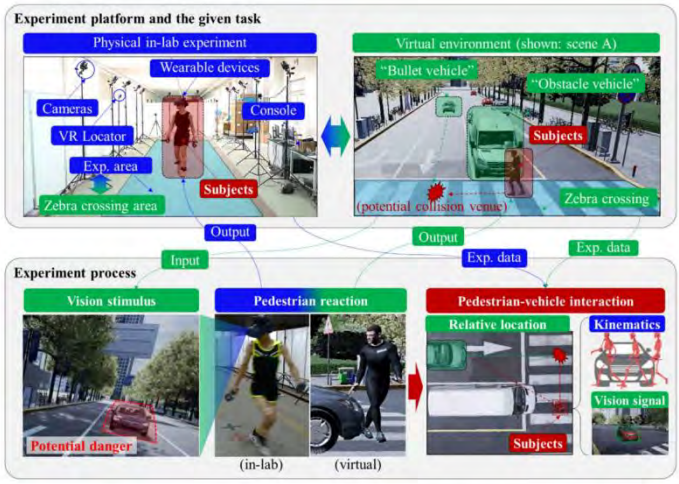

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Kinematics capture system. The kinematic capture system (No. Mars 2H; Beijing Nokov Science & Technology Co., Ltd) recorded the key motion information of subjects during the experiments. Setup of the kinetic capture system consists of 12 cameras, 54 on-body markers and a software module. The cameras (sampling frequency: 100 Hz) were fixed on the edge of the subjects' movement range by tripods. Motion of the subject throughout the whole event was recorded using 54 markers adhered externally to the skin on body. Algorithm processing of the kinematic images yielded signals of the quantified whole-body kinematics. Feature velocity of the pedestrian was extracted at the centre of the pelvis.

Citation Nie B, Li Q, Gan S, et al. Safety envelope of pedestrians upon motor vehicle conflicts identified via active avoidance behaviour[J]. Scientific reports, 2021, 11(1): 3996.

Link https://www.nature.com/articles/s41598-021-82331-z

仿真技术在足球整体进攻训练中的应用

关键词

足球运动；模拟仿真；编程；整体进攻

摘要

仿真技术优势明显,在足球运动应用领域有着广阔前景。目前足球进攻训练大多以直观、经验和现场实践为主,缺少专业化的情景再现和系统化的理论支持。利用 VisualC++开发平台和计算机模拟仿真编程设计方法将足球训练虚拟化,再现不同比赛训练场景下足球整体进攻演练。结果显示仿真技术实现的训练情境远多于实际,可作为足球整体进攻训练的辅助工具,丰富足球整体进攻的训练手段,帮助球员准确理解战术体系,推动足球训练的科学化发展。

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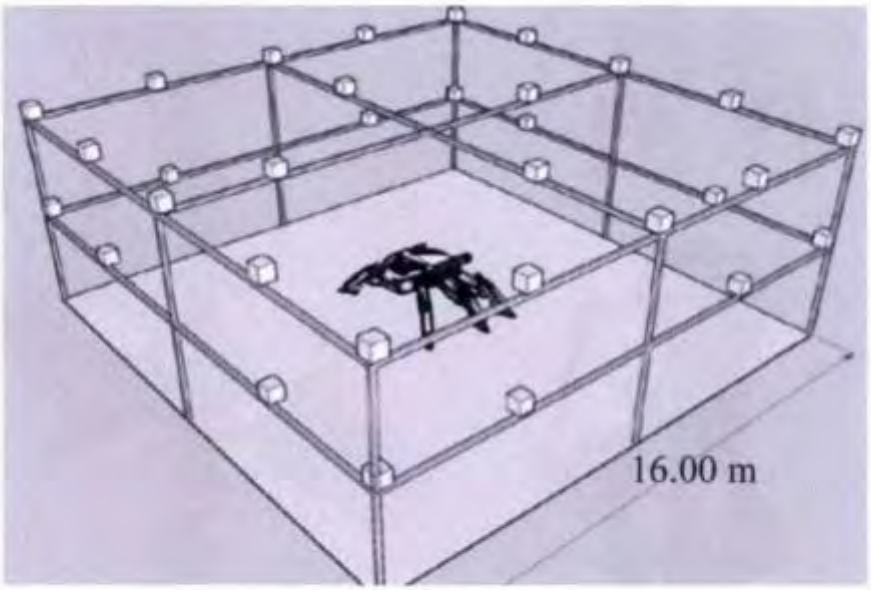

图 4　动作捕捉场地

Fig. 4　Motion capture field

NOKOV 度量动作捕捉在研究中的应用摘录

选取一个如图 4(由 NOKOV 度量光学三维动作捕捉公司提供)所示的动作捕捉场地并在场地内构造一个三维坐标系,用以记录场地内各个坐标点的位置变化。

引用格式 许诺，刘双龙，姜付高.仿真技术在足球整体进攻训练中的应用[J].系统仿真学报，2020,32（12）：2449-2460.DOI：10.16182/j.issn1004731x.joss.20-FZ0577.

链接

https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFDLAST2021&filename=XTFZ202012018&v=MDk3NjFyQ1VSN2lmWU9ScEZ5N2hWYnJCUFRuTmRMRzRITkhOcIk5RWJJUjhIWDFMdXhZUzdEaDFUM3FUcIdNMUY=

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基于混合现实技术的交互式教学应用研究——以中华毽课程为例

关键词

混合现实；体育项目；中华毽；交互式教学；虚拟互动

摘要

将混合现实（Mixed reality，MR）技术应用于中华毽体育教学实现了教师动作的数字化展示、多角度示范、虚拟互动训练等功能，初步解决了视频透视技术、光学动作捕捉技术数字人技术等在数字教学系统中的应用问题。MR 用户界面和视觉效果被显著地优化，学习者佩戴 MR 设备,可在虚实融合空间内近距离观察和模仿标准动作,体验踢毽乐趣。MR 系统存在的环境光匹配、姿态和触觉问题将进一步解决。MR 技术成功应用于中华毽教学将显著提高教学效果，也适合于其他类传统体育项目的普及和推广。

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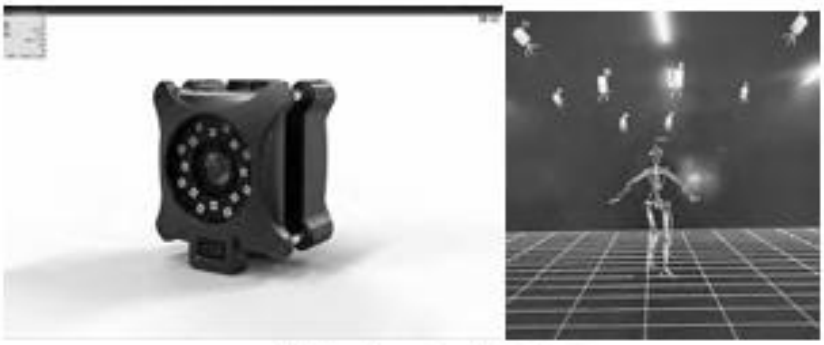

图 5 动捕设备配套的软件界面

（资料来源：NOKOV 度量光学官网及作者自绘）

NOKOV 度量动作捕捉在研究中的应用摘录

使用 NOKOV 度量光学动作捕捉系统，在运动员身上绑定 53 个关节点后开启录制流程，每秒采样 60 次。

引用格式 姚舜,唐彦,励羽欣等.基于混合现实技术的交互式教学应用研究——以中华毽课程为例[J].山西大同大学学报(社会科学版),2024,38(03):155-160.

链接
https://kns.cnki.net/kcms2/article/abstract?v=Uq4Diyda8XCPRF0TnCNLcPqNILeXZRUPv1pyxBdfR7O52FzIiCcfOZiiZFmdwCWSOpnM9K9HO3mpSmHo2jv0qwhni85yEW_3R8YPVDDed9osjeDzrc2GBAZzaLbxV7Ge&uniplatform=NZKPT&language=gb

虚拟现实中的大场景真实行走漫游研究

关键词

虚拟现实；真实行走；虚拟场景映射；等距扭曲；重定向行走；多人物理交互；自动防撞

摘要

计算机图形学之父 Ivan Sutherland 将虚拟现实视为一种终极的显示模式。虚拟现实通过为用户提供视觉、听觉以及触觉等多感官的信息模拟与刺激,使用户完全沉浸到由计算机模拟生成的虚拟世界当中,但仍感觉自己仿佛在现实中一样。对于虚拟现实技术来讲,如何为用户提供更加真实的模拟体验,如何让用户能够更加自然的与虚拟世界进行交互,是非常重要而且热门的研究课题。从一个地方移动到另一个地方是人们在日常生活中最常见的一项活动,因此也是虚拟现实中最为普遍和常用的一项交互方式。通过在现实空间中真实行走的方式漫游虚拟场景,能够为用户提供更加真实的沉浸感和更好的用户体验。然而这并不是一件很轻松的事情。在虚拟现实应用中让用户进行真实行走漫游主要有两大难点:（1）如何让用户在比现实空间区域更大的虚拟场景中自由的进行漫游；（2）如何在多个用户在同一现实空间中进行漫游时防止用户间发生碰撞以保证用户安全。针对真实行走漫游中的两大难点,本文提出了两种基于场景映射的真实行走漫游方法和一种支持多用户同时行走漫游与物理交互的自动避障方法。

为了使用户能够在比现实空间区域更大的虚拟场景中自由的进行漫游,场景映射的方法能够提供非常有效的技术支持。然而当虚拟场景远大于现实空间中用户可以行走的区域时,现有的场景映射方法会造成原始虚拟场景失真变形,影响用户漫游时的行走体验和视觉体验。为了在虚拟场景尺度远大于现实空间的情况下得到具有低等距扭曲的场景映射,本文提出一种分而治之的映射方法,名为分块映射。首先我们对虚拟场景的道路进行分块并分组。对于每组道路块,我们在维持相邻道路块在连接处光滑连续的前提下,通过最小化映射的等距扭曲能量得到的它的映射。我们把分好的道路块一组接着一组的映射到现实空间内部后,再对整个场景的映射进行一次全局优化,进一步降低整个映射的等距扭曲。分块映射方法对于虚拟场景与现实空间尺度差别极大时仍能生成高质量的场景映射,远远优于现有的其它方法,大量的用户调研与对比实验的结果验证了这一点。虽然分块映射的等距扭曲在数值上能维持一个较低的水平,但会将虚拟场景中的道路映射得十分弯曲,影响用户漫游时的视觉体验。为了进一步提升场景映射的质量,为用户提供更好的漫游体验,本文提出了另一种场景映射方法,名为重定向映射。该方法的主要思想是将重定向行走技术和光滑映射技术相结合,充分利用两者的优势。我们先使用分块映射,将虚拟场景中的道路映射到现实空间内部作为用户的指导路径。然后将重定向行走操作的阈值作为约束,进一步对分块映射进行优化,得到具有更低扭曲的场景映射。通过在用户漫游行走时对其进行重定向操作,使得用户的行动在被完全限制在现实空间内部的同时,能够漫游视野更加广阔扭曲形变程度更低的映射虚拟场景。相比现有的其它光滑映射技术,重定向映射能够提供更好的漫游体验。

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在多用户虚拟现实应用中,如果用户处于同一现实空间中,就会存在相互碰撞的风险。本文提出了一种新的自动防碰撞技术,能够支持虚拟现实应用中多人同时真实行走漫游虚拟场景,并且支持用户之间进行物理交互。在我们的系统中,多个用户可以在同一个小的现实空间中通过真实行走的方式漫游场景。在漫游的过程中,用户能够与其他的用户或者现实空间中的其它道具进行交互。为了使用户之间能够进行交互,我们需使用场景映射的方法来支持真实行走漫游。而场景映射会使场景中的道路发生重叠,多个用户在漫游时存在碰撞的风险。为了规避用户碰撞的风险,本文提出了一种利用动态虚拟化身进行辅助的自动避障技术。这些虚拟化身能够自然的出现,移动,以及消失,尽可能不对用户的行走体验产生干扰。本文进行了大量的用户调研实验来验证了多人系统的实用性和稳定性。

NOKOV 度量动作捕捉在研究中的应用摘录

1. 硬件设备
（ 1）跟踪定位系统
如图 4.5 所示，我们的使用 12 台 Nokov 动作捕提相机将一块 10mx10m 的区域搭建为一个跟踪定位区域。在这块区域中有一根铁柱（见图 4.5(b)），我们将它作为一个现实空间内部的障碍物（图 4.5(a）中的黑色方块），映射 f(V)需要对其进行避障。在漫游过程中用户的路径被重定向到 f(V)中，因此他们能够自由的行走而不会与铁柱发生碰撞。用户的头上会放置三个标记点，通过用动态捕捉相机定位这三个标记点并用其平均位置来作为用户的位置。

引用格式 董智超. 虚拟现实中的大场景真实行走漫游研究[D]. 中国科学技术大学,2020.DOI:10.27517/d.cnki.gzkju.2020.001795.

链接
https://kns.cnki.net/kcms2/article/abstract?v=3uoqIhG8C447WN1SO36whLpCgh0R0Z-iszBRSG4W40qHYXhao9i2hsvxwHGgifdaQ0_kIRYcezwE7es4gzKDsfo0jXqN98VS&uniplatform=NZKPT

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Part IV Entertainment

A Study on Using Three-dimensional Motion Capture to Teach and Evaluate Latin Dance Techniques of Forward Walk followed by Swing

Keywords

motion capture technology, Latin dance, teaching evaluation, movement analysis, center of gravity

Abstract

In recent years, many scholars have conducted in-depth research on classroom teaching reform as China's education reform has been deepening. Although there are certain achievements in sports dance education and teaching, it is still worthy of further exploration and empirical research on how to use appropriate and effective teaching methods in the classroom teaching as guided by the education reform in the new era, to make the education evaluation more scientific, professional and objective by combining modern information technology with education teaching in-depth. In this study, the three-dimensional motion capture is applied to the teaching of Latin dance in colleges and universities. The author selects excellent Latin dancers' (n=6), uses their forward walk with swing technical movements as the teaching content, and makes movement analysis with image processing technology. In this study, the students (n=20) of the sports dance elective course at Guangzhou Sport University are selected as the experimental subjects, and they are compared and analyzed through the teaching effect of the two groups after 8 weeks of teaching experiment. According to the results of the study, (1) after analyzing the excellent Latin dancers' movements, the technical movements of the forward walk followed by swing can be divided into 6 phases, and each phase has different technical characteristics; (2) after the teaching experiment, two groups show significant differences in the technical scores of Latin dance movements ($P<0.01$) by analyzing two groups of students' displacement changes of the center of gravity in technical movements, compared with the experimental group, the excellent Latin dancers' group has less offset in the X-axis direction, less change in vertical displacement in the Z-axis direction, and less speed in the Y-axis direction in the ending phase, their body trunk is close to vertical in the swing phase. All of these reflect better control of the center of gravity and smooth and stable movements, which are in high agreement with the movement scoring results. Conclusion: It is of guiding significance to apply three-dimensional motion

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capture to the teaching of technical movements of sports dance, and it is a positive reference for the objective evaluation and quantification of technical movements.

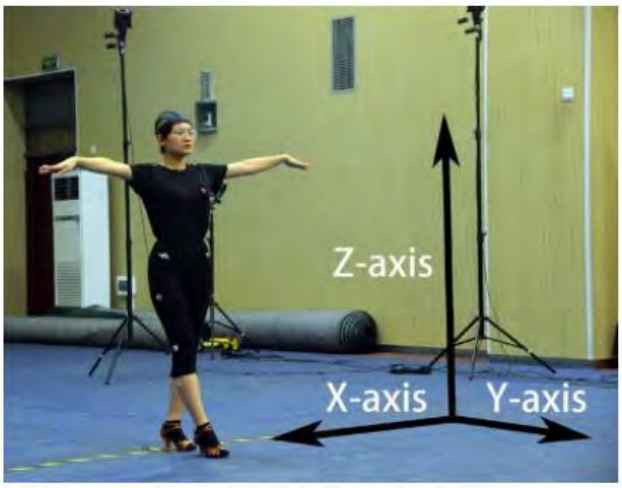

Figure 1 Definition illustration of the 3D axes of the motion capture area

How NOKOV Contributes to the Research

Experimental instrument and method for motion analysis In this experiment, 3D motion capture equipment (Nokov, China) is used for kinematic analysis of the movements, with a data acquisition frequency of 200 frames/second and resolution of 2352×1728 pixels. The test is performed in the sports biomechanics laboratory of the Experimental Building of Guangzhou Sport University.

Citation Yang H, Lv C. A Study on Using Three-dimensional Motion Capture to Teach and Evaluate Latin Dance Techniques of Forward Walk followed by Swing[C]//2022 2nd International Conference on Information Technology and Contemporary Sports (TCS). IEEE, 2022: 62-69.

Link https://ieeexplore.ieee.org/abstract/document/9918711

Encoded Marker Clusters for Auto-Labeling in Optical Motion Capture

Keywords

Optical motion capture, auto-labeling, marker clusters, linear block code

Abstract

Marker-based optical motion capture (MoCap) is a vital tool in applications such as virtual production, and movement sciences. However, reconstructing scattered MoCap data into real motion sequences is challenging, and data processing is time-consuming and labor-intensive. Here we propose a novel framework for MoCap auto-labeling and matching. In this framework, we designed novel clusters of reflective markers called auto-labeling encoded marker clusters (AEMCs), including clusters with an explicit header (AEMCs-E) and an implicit header (AEMCs-I). Combining cluster design and coding theory gives each cluster a unique codeword for MoCap auto-labeling and matching. Moreover, we provide a method of mapping and decoding for cluster labeling. The labeling results are only determined by the intrinsic characteristics of the clusters instead of the skeleton structure or posture of the subjects. Compared with commercial software and data-driven methods, our method has better labeling accuracy in heterogeneous targets and unknown marker layouts, which demonstrates the promising application of motion capture in humans, rigid or flexible robots.

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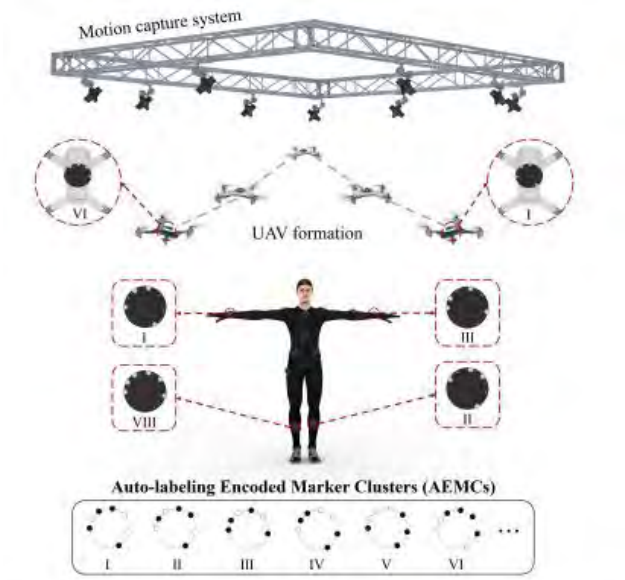

Fig. 1. A depiction of applications of AEMCs. (1) Unmanned Aerial Vehicle (UAV) formation (top). By attaching the different clusters to the UAVs, the real-time pose of each UAV can be automatically captured from the MoCap system. The position data can be the source for position estimation during UAV flight or validation of UAV formation control algorithms. (2) Human motion capture (middle). The human skeletal motion sequence can be reconstructed by attaching the different clusters to the joints of the human body. *Character model is generated using Mixamo(Adobe, 2024).* At the bottom, schematics of part of AEMCs are shown.

How NOKOV Contributes to the Research

We measured the minimum resolution dm, systematic error e, and minimum spacing of designed radius ΔR of the MoCap system (Mars Series, NOKOV Science & Technology, Beijing, CN) for reflective markers of two different sizes. Based on these parameters, we designed the AEMCs-I and AEMCs-E for experimentation, with their specific parameters detailed in Table 2.

Citation Wang H, Hou T, Liu T, et al. Encoded Marker Clusters for Auto-Labeling in Optical Motion Capture[J]. ACM Transactions on Graphics, 2025, 44(2): 1-16.

Link https://dl.acm.org/doi/10.1145/3716847

Folk dance motion templates based on motion capture technique for guaranteeing authenticity of folk Dance: Case studies of Malay folk dances

Abstract

Both tangible and intangible cultural heritages are crucial to be preserved and conserved due to their reflections to the history and identity of certain countries (Mazian et al., 2023). Intangible cultural heritage (ICH) involves the human action that can be observed, felt, tasted, smelled or heard during the performance, and cannot be appreciated when lost or disappeared (Mustafa and Saleh, 2017). Performing arts, customs and culture, oral traditions, fine arts or crafts, knowledge and practice, and living heritage can be categorised in ICH.

Folk dance (FD) is one of ICH that originates from customs and cultural practices of a particular community or region (Pálya and Kiss, 2024; Liu et al., 2024). These FDs are typically passed down through generations for performing rituals and developing bonds with each other (Giannoulakis et al., 2018). Each FD has its own messages, stories, music, costumes and dance moves (Li et al., 2019).

Issues on FDs caused by the lack of interest (Mazian et al., 2023) and the limitations of human demonstration, text documentation, and video in teaching and learning methods (Selmanović et al., 2019) have significant impacts in the form of loss, neglect, extinction, and destruction of this valuable heritage. Therefore, the implementation of digitization and visualization of FDs using motion capture techniques are crucial in order to preserve and conserve ICH.

Motion capture (MoCap) is one of the most effective methods for digitizing ICH, including FDs (Li et al., 2019). MoCap is the process of recording the movement of objects or people and translating these movements into digital models (Cai et al., 2023; Loupas et al., 2024; Zhang et al., 2022). This process involves mathematical terms using tracking a number of key points in space over time in order to obtain a single 3D representation of the performance (Wan Idris et al., 2019a). This is because MoCap enables the translation of live motion into a digital performance (Wan Idris et al., 2018, 2019b; Hisham et al., 2020). In FDs, MoCap have been utilized in various purposes such as for tracking the movements of dancers and converting into a structured format (Cai et al., 2023; Loupas et al., 2024), for recording and preserving the movements of dancers performing traditional dances (Zhang et al., 2022), for studying the dynamic balance in dances (Pálya and Kiss, 2024), for applying in animation, sports science and dance analysis (Liu et al., 2024). These purposes can be implemented well

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because MoCap can produce motion templates of FDs. The motion templates are predefined movements or poses that are captured using MoCap technology (Hachaj et al., 2017; Müller and Röder, 2006; Bobick and Davis, 2001) and can serve as a guidance, benchmark and reference for dancers to learn and perform choreography. However, besides the capabilities and significance of MoCap techniques in producing the motion templates of FDs, the originality and authenticity of FDs should be also emphasised. Therefore, the created motion templates of FDs need to be evaluated as well.

This paper presents in detail on how to develop and evaluate the motion templates of FDs using MoCap technique for ensuring their authenticity in order to preserve and conserve the intangible cultural heritage. Section 2 discusses the related works on MoCap techniques used in preserving FDs while Section 3 presents the methods and materials used in this study focusing on the selected Malay FDs and the proposed framework for creating the motion templates of FDs using MoCap. Analysis and results will be described in Section 4 while the last section presents the discussion and conclusion.

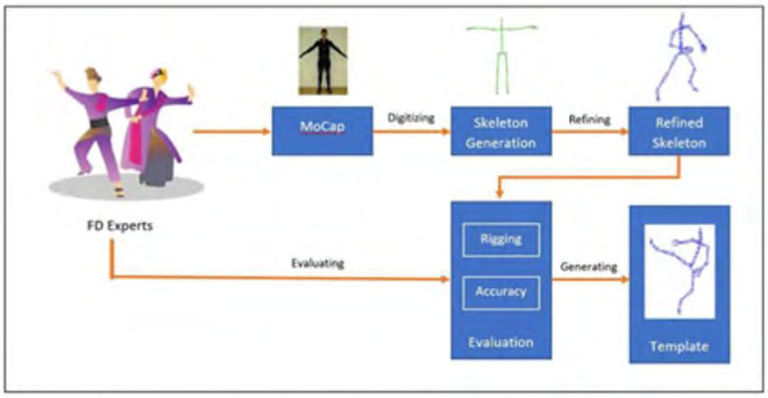

Fig. 1. Adapted framework for creating motion templates of FDs using MoCap (Mazian et al., 2023).

How NOKOV Contributes to the Research

Therefore, markerless MoCap systems present a more culturally sensitive and technically feasible alternative. Devices such as Vicon Markerless, Theia3D, NOKOVMarkerless, AR51 Real-Time Markerless, and BEAMoCap enable motion tracking without suits or markers, allowing dancers to perform naturally in traditional costumes. These systems employ advanced computer vision and AI to deliver accurate skeletal tracking, and they are better suited for capturing performances in both controlled and community-based settings.

Citation Rizhan W, Mazian A I, Rahim N, et al. Folk Dance Motion Templates based on Motion Capture Technique For Guaranteeing Authenticity of Folk Dance: Case Studies of Malay Folk Dances[J]. Digital Applications in Archaeology and Cultural Heritage, 2025: e00449.
Link https://www.sciencedirect.com/science/article/abs/pii/S2212054825000517

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Synchronize Dual Hands for Physics-Based Dexterous Guitar Playing

Keywords

character animation, hand animation, physics-based control, dexterous control, motion synthesis, multi-agent reinforcement learning, cooperative learning, motion capture dataset

Abstract

We present a novel approach to synthesize dexterous motions for physically simulated hands in tasks that require coordination between the control of two hands with high temporal precision. Instead of directly learning a joint policy to control two hands, our approach performs bimanual control through cooperative learning where each hand is treated as an individual agent. The individual policies for each hand are first trained separately, and then synchronized through latent space manipulation in a centralized environment to serve as a joint policy for two-hand control. By doing so, we avoid directly performing policy learning in the joint state-action space of two hands with higher dimensions, greatly improving the overall training efficiency. We demonstrate the effectiveness of our proposed approach in the challenging guitar-playing task. The virtual guitarist trained by our approach can synthesize motions from unstructured reference data of general guitar playing practice motions, and accurately play diverse rhythms with complex chord pressing and string picking patterns based on the input guitar tabs that do not exist in the Citation. Along with this paper, we provide the motion capture data that we collected as the reference for policy training. Code is available at: https://pei-xu.github.io/guitar.

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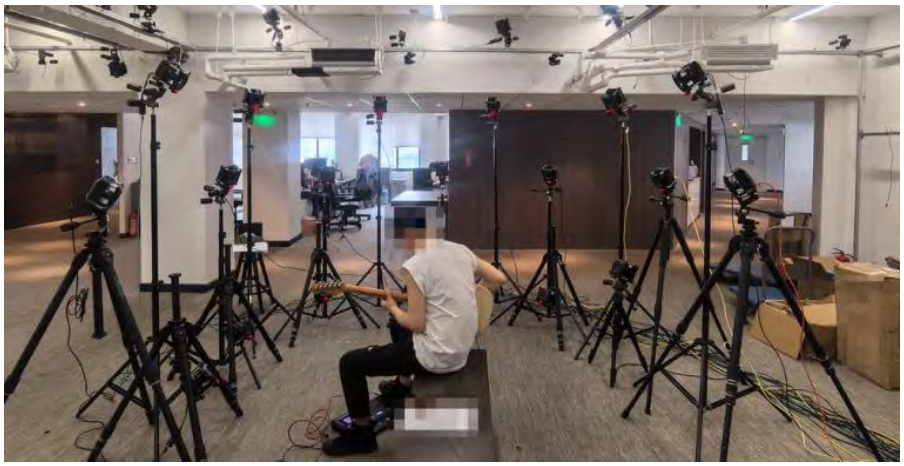

How NOKOV Contributes to the Research

We took the motion capture solutions provided by NOKOV and em ployed 18 infrared cameras for motion capture, 7 of which have a resolution of 9MP and 11 have a resolution of 4MP. We placed 19 markers on each hand of the subject, and 4 markers on the guitar for localization. All data were captured at 120FPS. The camera deployment and marker placement are exhibited in Fig. S1.

Citation Xu, Pei, and Ruocheng Wang. "Synchronize dual hands for physics-based dexterous guitar playing." SIGGRAPH Asia 2024 Conference Papers. 2024.

Link https://arxiv.org/abs/2409.16629

Tailored Reality: Perception-aware Scene Restructuring for Adaptive VR Navigation

Keywords

retargeting, perception, Virtual reality

Abstract

In virtual reality (VR), the virtual scenes are pre-designed by creators. Our physical surroundings, however, comprise significantly varied sizes, layouts, and components. To bridge the gap and further enable natural navigation, recent solutions have been proposed to redirect users or recreate the virtual content. However, they suffer from either interrupted experience or distorted appearances. We present a novel VR-oriented algorithm that automatically restructures a given virtual scene for a user's physical environment. Different from the previous methods, we introduce neither interrupted walking experience nor curved appearances. Instead, a perception-aware function optimizes our retargeting technique to preserve the fidelity of the virtual scene that appears in VR head-mounted displays. Besides geometric and topological properties, it emphasizes the unique first-person view perceptual factors in VR, such as dynamic visibility and objectwise relationships. We conduct both analytical experiments and subjective studies. The results demonstrate our system's versatile capability and practicability for natural navigation in VR: It reduces the virtual space by 40% without statistical loss of perceptual identicality.

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(a) Tracking system (b) A real capture

Fig. 10. Experimental setup. Eight motion capture cameras are used to track the users' positions (a). During walking, the laptop and power supply are in the basket carried by users (b).

How NOKOV Contributes to the Research

Space and positional tracking.The size of our physical workspace Pis 5.6 m×5.6 m, as shown in Figure10(a). Eight Nokov motion capture cameras locate the users with 3 markers on their heads (Figure10). There are no physical obstacles inside P.

Citation Dong Z C, Wu W, Xu Z, et al. Tailored reality: Perception-aware scene restructuring for adaptive vr navigation[J]. ACM Transactions on Graphics (TOG), 2021, 40(5): 1-15.

Link https://dl.acm.org/doi/10.1145/3470847

The Application of Digital Technology in the Protection of Intangible Cultural Heritage — Taking Beijing Palace Carpets as an Example

Keywords

Beijing palace carpet, Intangible cultural heritage, Digital technology.

Abstract

The patterns, decorations and exquisite skills of Beijing palace carpets show the meaningful national culture that is passed down through body language and oral instruction. They are not only a concrete display of ancient people's world view, outlook on life, and values, but also convey image language and textual information related to natural science and cultural knowledge. As one of the typical intangible cultural heritage, the protection and inheritance of Beijing palace carpets must be based on the principle of "taking the protection as the principal thing, rescuing firstly, using rationally, and inheriting and developing", so as to record, research and inherit the representative skills, original hand-drawn draft maps, textures and materials and even the body language of the inheritors of Beijing palace carpets in a comprehensive and brand-new way; at the same time, at the moment when digital technology is involved in social development, Beijing palace carpets, as an integral part of cultural inheritance and development, should also explore ways and methods to achieve innovative transformation and creative development.

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How NOKOV Contributes to the Research

The Chinese motion capture system manufacturer Nokov is accurate and easy to use, which is more suitable for the motion capture of the Beijing palace carpet inheritors. Its collector is close to everyday clothes, light and comfortable to wear without complicated circuits, and it captures the details of the inheritor's motions with precision. The process of Beijing palace carpet is complicated. Each step of the technical motions such as slitting, spinning, twisting, under painting, through the weft, off the machine, flattening and trimming, etc. can be meticulously recorded by the Nokov (Nokov motion compensation system).

Citation Jiang B. The Application of Digital Technology in the Protection of Intangible Cultural Heritage—Taking Beijing Palace Carpets as an Example[C]//2021 Conference on Art and Design: Inheritance and Innovation (ADII 2021). Atlantis Press, 2022: 35-40.

Link https://www.atlantis-press.com/proceedings/adii-21/125970447

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Transformer IMU Calibrator: Dynamic On-body IMU Calibration for Inertial Motion Capture

Abstract

In this paper, we propose a novel dynamic calibration method for sparse inertial motion capture systems, which is the first to break the restrictive absolute static assumption in IMU calibration, i.e., the coordinate drift RG′ G and measurement offset RBS remain constant during the entire motion, thereby significantly expanding their application scenarios. Specifically, we achieve real-time estimation of RG′ G and RBS under two relaxed assumptions: i) the matrices change negligibly in a short time window; ii) the human movements/IMU readings are diverse in such a time window. Intuitively, the first assumption reduces the number of candidate matrices, and the second assumption provides diverse constraints, which greatly reduces the solution space and allows for accurate estimation of RG′ G and RBS from a short history of IMU readings in real time. To achieve this, we created synthetic datasets of paired RG′ G, RBS matrices and IMU readings, and learned their mappings using a Transformer-based model. We also designed a calibration trigger based on the diversity of IMU readings to ensure that assumption ii) is met before applying our method. To our knowledge, we are the first to achieve implicit IMU calibration (i.e., seamlessly putting IMUs into use without the need for an explicit calibration process), as well as the first to enable long-term and accurate motion capture using sparse IMUs. The code and dataset are available at https\://github.com/ZuoCX1996/TIC.

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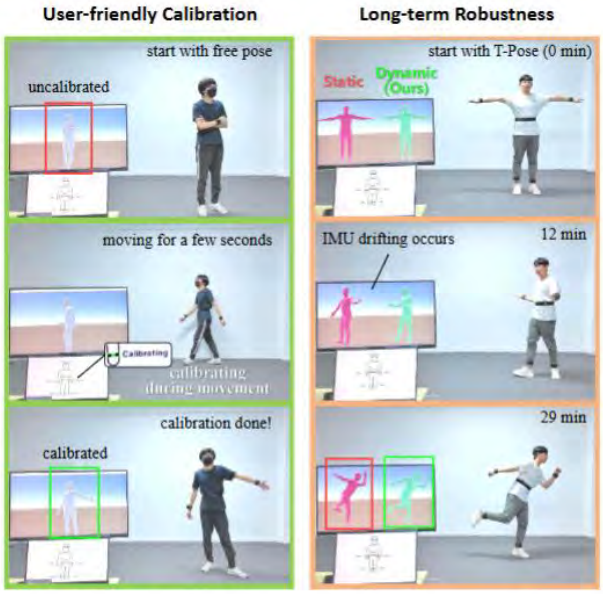

Fig. 1. Live demonstration of our *dynamic* calibration method against the conventional *static* calibration method. Our method provides a user-friendly experience (**w/o IMU heading reset and T-Pose**) and ensures long-term robustness for inertial motion capture.

How NOKOV Contributes to the Research

5.2 Test Data Collection
We recruited 5 volunteers (3 male, 2 female) to collect the real-world dataset. All these volunteers have experience with using inertial motion capture devices and are familiar with the process of Static Calibration. Volunteers were asked to wear both optical motion capture suits and 6 IMUs simultaneously, placed on the left forearm, right forearm, left lower leg, right lower leg, head, and hips (see Fig. 5). All 6 IMUs are integrated with 3 optical markers, allowing the absolute orientation and acceleration of IMUs to be captured. We collect continuous 60-minute data at 60 fps for each volunteer, which is sufficient to capture drift signals of IMUs and ensure volunteers do not overexert themselves. In each session, volunteers sequentially perform stretching, walking/running/jumping, table tennis, aerobics, boxing, and free activity, each lasting 10 minutes. IMU data are recorded using the NOLTOM Axis Lab system and calibrated through Static Calibration before system start-up. Human body pose, absolute IMU orientation and acceleration are obtained using the NOKOV motion capture system.

Citation Zuo C, Huang J, Jiang X, et al. Transformer IMU calibrator: dynamic on-body IMU calibration for inertial motion capture[J]. ACM Transactions on Graphics (TOG), 2025, 44(4): 1-14.

Link https://dl.acm.org/doi/10.1145/3730937

基于动作捕捉技术的虚拟仿真模特展示姿态的研究

关键词

动作捕捉技术；虚拟模特；Style3D；走秀姿态

摘要

随着动作捕捉技术的迅速发展，虚拟时尚展示已成为当前学术研究领域的热点。 文章以真人模特为案例样本， 使用动作捕捉技术,提取真人模特走秀的路径数据，并通过 Maya 软件对数据进行处理和骨骼重定向，使数据适配虚拟模 特，进而以虚拟模特的形式，在 Style3D 中实现了服装制版、穿衣试衣、形象设计以及场景搭配等仿真展示和虚拟走秀。

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图 1 走秀动作数据的捕捉与采集现场图(由作者拍摄于 NOKOV 深圳分公司)

NOKOV 度量动作捕捉在研究中的应用摘录

本次实践案例选取了惠州学院服装表演专业学生朱梦丽作为真人模特样本，使用了 NOKOV（ 度量） 光学三维动作捕捉系统，在模特身上的关节与躯干处贴标记点（见图 1），通过系统返回点的高精度定位信息，计算出模特走秀时的动作轨迹数据

引用格式 张新宁,佘婕,洪勤真.基于动作捕捉技术的虚拟仿真模特展示姿态的研究[J].轻纺工业与技术,2024,53(06):111-114.

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数字技术背景下临朐桑皮纸非遗传承与推广路径研究

关键词

数字化；临朐桑皮纸；传承与推广

摘要

桑皮纸是纸术的活化石，千年不朽，色泽恒常，虫蛀难侵，承载了中华民族千年造纸的智慧，是窥探纸文化历史的窗口。临朐桑皮纸具备耐磨耐折、柔韧细长的特点，是山东非遗的璀璨明珠。临朐桑皮纸捞纸技艺，源自祖辈口传心授，无文字记录，目前面临失传的困境。作为中华文化的瑰宝，临朐桑皮纸亟须保护与传承。本文深入探讨了数字技术背景下临朐桑皮纸非遗传承与推广的路径，以期让临朐桑皮纸焕发新活力，实现非遗文化的活态传承。

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NOKOV 度量动作捕捉在研究中的应用摘录

首先，借助“NOKOV”这一尖端光学技术，对桑皮纸制作的每一道工序进行细腻入微的捕捉，确保每一个动作、每一次操作都能精准无误地转化为数据。随后，这些数据将被实时导入先进的仿真软件中，通过虚拟现实（VR）与增强现实（AR）技术的融合，构建出一个生动逼真的技艺体验空间。公众得以身临其境，感受桑皮纸制作过程中的每一个细节，领略其独特的美学魅力与匠人精神的艰辛付出，从而激发对这项传统技艺的浓厚兴趣与深切敬意。其次，相关部门可开发一款集知识普及、互动体验与文创展示功能于一体的微信小程序。用户只需轻轻一点，即可穿越时空的界限，深入了解临朐桑皮纸技艺的悠久历史与精湛技艺。同时，精选一系列具有代表性的文创产品，通过数字化手段转化为独一无二的数字藏品，供用户珍藏与分享。最后，为实现对临朐桑皮纸技艺的全面保护与传承，相关部门可整合相关传承人的影像资料、成品样本及技艺数据，构建一座详尽而系统的档案数据库，成为地区非遗名录的重要组成部分，为后续的研究、保护与传承工作提供坚实的数据支撑。

引用格式 胡磊,史严梅.数字技术背景下临朐桑皮纸非遗传承与推广路径研究[J].新传奇,2024,(21):95-97.

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数字时代背景下舞蹈创作的创新性发展

关键词

音乐舞蹈；计算机软件及计算机应用

摘要

数字时代的迅猛发展对全球文化艺术领域产生了重大影响，舞蹈创作领域也不例外。数字时代背景下，舞蹈创作迎来了前所未有的创新性发展。数字化技术为舞蹈创作提供了更加广阔和多样的表现手段。数字技术包括虚拟现实、增强现实、运动捕捉等，数字技术可以有效地扩展舞蹈演出的表现空间和时空范围，从而大大拓宽了舞蹈创作的想象空间，也为舞蹈创作注入了新的活力。数字技术的运用不仅可以拓展舞蹈表现的形式，还可以使艺术家们感受到更新和更深刻的体验，更好地呈现出艺术家们的独特创意。

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图 1　动捕成像

图 2　设备调试

NOKOV 度量动作捕捉在研究中的应用摘录

在斯芬克斯元宇宙戏剧节中，由余尔格编排、表演的舞蹈作品《欢迎光临》（图 1、图 2），运用动作捕捉拍摄技术在 NOKOV 度量的支持下进行，NOKOV 自主研发的算法能够实时解算人体骨骼数据，无惧遮挡。在非现实的空间里，舞蹈动作经过动作捕捉映射到模型，模型在 3D 场景中运动，可能和创作者的想象出现很大"偏离"，这些客观因素导致的"偏离"在现实中都是不可能发生的，但是"偏离"和"不可控"同时也孕育了新的灵感和可能性。

引用格式 李进.数字时代背景下舞蹈创作的创新性发展[J].舞蹈,2023(03):98-100.

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https://kns.cnki.net/kcms2/article/abstract?v=3uoqlhG8C44YLTlOAiTRKu87-SJxoEJu6LL9TJzd50kMlrAbjzUr5bPTcwWht0L5Y46JUzAnDwln9XNmS_nhuERW_lDE055Z&uniplatform=NZKPT

中国式现代化进程中武术产业发展的现实意义、困境与策略

关键词

中国式现代化；武术产业；数字技术

摘要

在中国式现代化进程中，将武术作为一种民族传统文化产业进行高质量发展，对发展经济、传承与弘扬中华优秀传统文化有着重要的现实意义。文章从文化学和传播学视角入手，运用文献资料法和逻辑分析法等研究方法对武术产业发展进行深入探究。研究认为：当前武术产业仍处于起步阶段，存在武术产业保护机制不完善，武术产业链有待开发，武术产业技术有待提升，武术产品资源有待挖掘等困境，并提出相应对策。

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NOKOV 度量动作捕捉在研究中的应用摘录

技术是当前推动武术数字化转型的核心力量，已在武术产业发展的各个方面有所表现。梁同福在《数字化时代中国传统体育文化表征系统的研究》\[6]中提出，数字技术影响着中国文化的竞争力，各种文化形式之间的竞争首先体现为数字技术上的竞争：（1）在武术培训业中，可利用增强现实技术的交互式武术教学设备呈现逼真的武术场景和动作，引导学生进行练习，以 NOKOV 动作捕捉技术准确记录和分析武术动作；（2）提高对数字化生产要素的投入，并通过话题检测与跟踪对不同对象构建相应的系统可直接准确定位目标群体，有效提高传统武术的传播效率；（3）借助人工智能、全息成像、物联网等数字技术对基础设施进行转型升级，加强"数字＋武术产业"深度融合，引入智能化设备和传感器，监控武术场馆的使用情况、设备状态和安全问题，提高设施管理的效率和安全性。

引用格式 张琪琳,洪浩,祝君宇.中国式现代化进程中武术产业发展的现实意义、困境与策略[J].武术研究,2025,10(03):35-37.DOI:10.13293/j.cnki.wskx.011011.

链接

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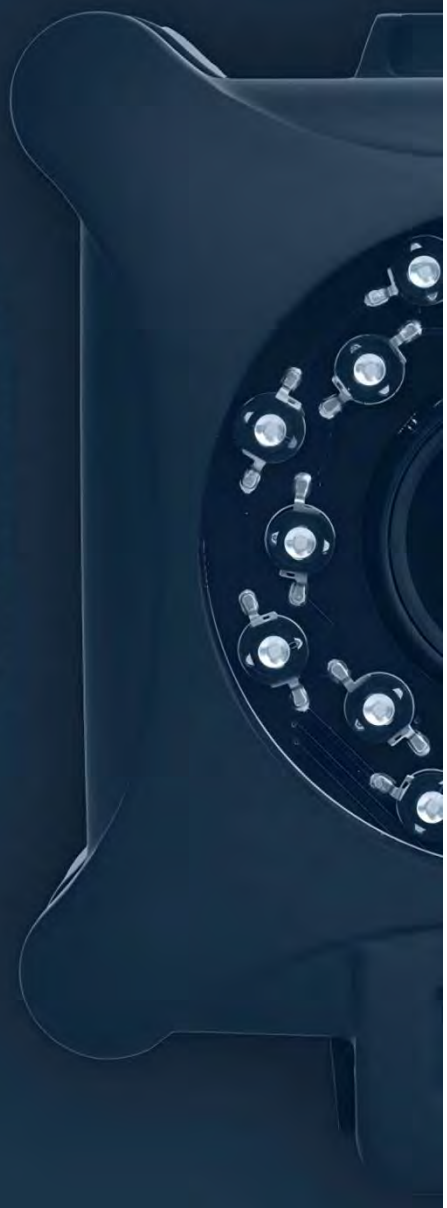
NOKOV Motion Capture System



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