

Research Progress on Navigation and Localization Technologies of Autonomous Mobile Robots: Methods, Applications and Future Trends

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Abstract. Autonomous mobile robots act as vital technical carriers in scenarios including intelligent manufacturing, smart logistics, unmanned inspection and public services, and their stable operation relies on reliable localization, mapping, navigation and path planning capabilities. Centered on navigation and localization technologies for autonomous mobile robots, this paper delivers a comprehensive review. It systematically sorts out the developmental context of sensor-based localization methods, Simultaneous Localization and Mapping (SLAM), visual odometry, multi-sensor fusion and emerging intelligent algorithms. Combined with typical application scenarios such as warehouse robots, unmanned aerial vehicles and service robots, this paper analyzes the applicable conditions of various technical routes. Relevant research reveals that navigation and localization systems for mobile robots are gradually transforming from single-sensor and rule-based algorithms into an integrated framework integrating multi-source perception, probabilistic estimation, graph optimization, semantic understanding and intelligent planning. Nevertheless, deficiencies still exist in robustness under dynamic environments, long-term operational stability, low-cost high-precision fusion, real-time path decision-making and cross-scenario generalization. Future research shall further strengthen capacities including collaborative multi-sensor perception, semantic map construction, lightweight computation, degraded scene recognition and safety-constrained planning, so as to advance autonomous mobile robots toward high precision, strong robustness, low cost and large-scale deployability.

Keywords: autonomous mobile robot, navigation and localization, Simultaneous Localization and Mapping, multi-sensor fusion, path planning

1. Introduction

1.1. Research background

With the advancement of science and technology, robotics technology keeps evolving, which brings fundamental transformations to traditional industrial production [1]. As a product of such technological progress, mobile robots possess intelligence unmatched by conventional robots, embodying the latest achievements of computer technology and artificial intelligence. Different

from traditional manufacturing environments, the working scenarios of mobile robots feature uncertainties and unstructured characteristics, thus mobile robots require external environmental perception and local autonomous planning capacities [2]. For this reason, navigation and localization serve as core technologies for intelligent mobile robots. It can be stated that reliable navigation systems and accurate perception capabilities constitute the prerequisite for mobile robots to realize practical value and better serve human society. Accelerated social rhythms raise increasingly stringent requirements on production efficiency, and deploying robots to replace human labor becomes a core approach to efficiency improvement. At present, mobile robot technologies have been applied across all walks of life and can be spotted in most daily fields. Warehouse robots at express delivery stations and unmanned aerial vehicles that help humans explore broader landscapes all depend on mobile robot technologies, among which navigation and localization stand as the core guarantee for their stable and successful operation.

1.2. Research problems

Core research problems of mobile robots fall into three categories: where the robot is located, where the robot intends to arrive, and how the robot can reach the target position [1]. Based on these fundamental problems, key technologies for mobile robots cover environmental perception, perceptual information fusion, path planning and robot localization. Although mobile robot technologies keep advancing with the times, various technical defects and challenges persist. Scholars keep subdividing such problems and tackling them one by one. An overview of current conditions and pending challenges in the field of mobile robot navigation and localization identifies major issues: redundant algorithms with low efficiency, underdeveloped algorithm logics, incomplete sensor functions, limited environmental perception capacity of mobile robots, and insufficient navigation and localization accuracy. All the above aspects represent critical directions for further research and optimization.

1.3. Research methodology

Navigation and localization technologies for mobile robots have achieved certain developmental outcomes, accompanied by both merits and inherent limitations. This paper conducts a review and analysis of the current state of such technologies. Starting from two dimensions of technical research and practical application, it sorts out existing research status and methodologies. Combined with analyses of real application scenarios, this paper systematically summarizes relevant content through literature review, classification, induction and comparative analysis of different technologies. It aims to provide references for research on robot navigation and localization technologies, facilitate technological advancement and offer orientations for follow-up research. The second section of this paper summarizes and analyzes navigation and localization methods for autonomous mobile robots. Practical applications of the technologies are elaborated in the third section, while the fourth section discusses future developmental trends. Finally, this paper concludes its research work and findings, and puts forward prospects for future development.

2. Navigation and localization methods for autonomous mobile robots

Against the backdrop of rapid artificial intelligence development, robotic technologies, especially mobile robots, have gained extensive applications in numerous fields. The selection of navigation and localization methods serves as a critical link to the autonomous movement function of robots. A

complete visual navigation system consists of three core components: a visual sensor module, a Simultaneous Localization and Mapping (SLAM) module, and a path planning module [3]. Long-standing research conducted by scholars on path planning, global localization, navigation strategies and other topics has boosted the development of this field [4]. This section mainly sorts out core technical approaches for navigation and localization of autonomous mobile robots. Starting from sensors and SLAM technologies, this paper extends the discussion to multi-sensor fusion and emerging algorithms, unfolds the evolution of relevant technologies step by step, analyzes features and limitations of different technologies, summarizes approaches to offset technical defects and improve navigation and localization performance, and sorts out various new technologies to demonstrate the current status and characteristics of this research area.

2.1. Sensor-based localization methods

Sensors can be regarded as the "eyes" of mobile robots in certain scenarios. Different localization methods determine distinct performance of such "eyes" to fulfill varied specific tasks. Zhang Yi et al. [5] proposed an inertial sensor-based pose localization and control method. This method can efficiently, accurately and stably cope with the complexity and uncertainty of industrial environments, reduce interferences including wind and vibration, and further cut down localization errors caused by such disturbances. To tackle the problem that robots suffer degraded environmental perception in complex environments filled with massive obstacles and thus fail to accurately follow preset moving routes, Xuan Chunqing et al. [6] studied a navigation and localization method based on sensor data feedback. Through analyzing robot environmental perception, navigation localization and experimental results, this method reduces the average tracking error of navigation and localization to 0.022 m, effectively boosting localization accuracy. Considering cost and power consumption constraints, Wang Junkai [7] started from human body electrostatic sensing principles and signal detection mechanisms. On the basis of the LSTM algorithm, he analyzed typical electrostatic signals, classic sensor designs and operating characteristics, and put forward a localization method combining electrostatic sensors and location fingerprints, offering a new technical solution for indoor localization.

Chen Jianwei [8] pointed out that mainstream technologies such as Zigbee, Wi-Fi, Bluetooth, ultrasonic and ultra-wideband commonly encounter bottlenecks in accuracy, environmental adaptability and cost. He further analyzed the feasibility of Visible Light Positioning (VLP), an upgraded technology derived from Visible Light Communication (VLC) based on light-emitting diodes (LEDs). He argued that VLP, featuring low cost, high precision, strong security and wide applicability, would become a major research direction in indoor localization, with the operating principles and characteristics of LEDs as the indispensable theoretical foundation of this technology. Zhu et al. [9] designed three controllers based on sensors: leg direction-based visual servoing, straight line-based visual servoing and image moment-based visual servoing, so as to guarantee the precision performance of triangular robots. Cheok et al. [10] introduced a novel indoor positioning and navigation information transmission system built on optical sensors. This system extends GPS tracking functions to indoor surroundings and lays a theoretical foundation for indoor guidance and navigation applications. Ashokaraj IAR et al. [11] equipped mobile robots with ultrasonic sensors and adopted interval analysis to handle nonlinear problems in a global manner, realizing robot navigation and localization. Yin Z et al. [12] proposed an indoor localization method for mobile robots based on depth cameras. The method completes localization via feature point extraction, feature matching and camera pose estimation, achieving an accuracy of 0.027 meters and satisfying indoor localization demands of mobile robots. Single-type sensors inevitably have inherent

drawbacks, while multi-sensor fusion can compensate for such defects mutually. To integrate multi-sensor information for complementary advantages, enhanced redundancy and stronger robot perception of complex environments, Xu Yihao [13] designed a multi-sensor fusion mapping and localization algorithm, which significantly optimizes localization outcomes. Chen LH et al. [14] combined classic Wi-Fi indoor positioning systems with Pedestrian Dead Reckoning (PDR) systems. The two systems complement each other's strengths and achieve higher positioning accuracy.

2.2. Simultaneous Localization and Mapping (SLAM)

Simultaneous Localization and Mapping (SLAM) technology [15] has been widely applied across multiple industries. The deployment of SLAM in mobile robotics enables robots to conduct real-time pose estimation, construct environmental maps and complete navigation, mapping and localization missions in complex surroundings, acting as a vital technical support for the intelligent technology sector [16].

SLAM algorithms are divided into two main categories according to adopted sensors: LiDAR SLAM and Visual SLAM (VSLAM) [17]. LiDAR SLAM boasts high precision and favorable real-time performance yet suffers high hardware costs and limited environmental information acquisition. VSLAM features lower costs and richer environmental data, and multi-sensor fusion has become the mainstream development trend of VSLAM in recent years. Nevertheless, its localization accuracy and mapping quality degrade severely under extremely strong or uneven illumination conditions [18]. Each type of SLAM algorithm has respective merits and demerits. Therefore, Xiao Huizhuo [18] researched SLAM methods based on ultrasonic sensors to remedy deficiencies in previous studies by Abadi et al. [19]. On the basis of their research, Xiao integrated odometers, inertial measurement units (IMUs) and other sensors to realize simultaneous localization and optimize global maps. Luo J et al. [20] held that it is difficult to substantially improve localization accuracy merely by increasing the number of particles required for precise map construction. Accordingly, they proposed a fast SLAM algorithm based on Ball Particle Filter (Ball-PF) and greatly elevated system performance via map matching and other auxiliary technologies. Traditional single-sensor SLAM systems have inherent limitations in practical deployment [21, 22]. To break through such restrictions, multi-sensor fusion technologies have been proposed. Qin Fuhong [23] conducted research and optimization on LiDAR-vision fusion SLAM algorithms. The improved algorithm strengthens localization and mapping capabilities as well as system robustness, providing a reliable solution for autonomous navigation of mobile robots. Chen PY et al. [24] proposed a deep learning-based end-to-end visual autonomous navigation system for robots, which combines semantic segmentation with SLAM to enhance robot perception capacity and allow robots to complete path planning and autonomous navigation relying solely on visual input. Wolf D F et al. [25] put forward an online SLAM algorithm tailored for dynamic environments. The algorithm can distinguish static and dynamic components within environments and mark them on constructed maps. Zhao X R [26] integrated IMU pre-integration theory with the Cardinalized Balanced Multi-Target Multi-Bernoulli (CBMeMBer) filter in a novel SLAM technology. This integration improves pose estimation precision of LiDAR point clouds and enables accurate, efficient robot navigation in complex environments. In a review paper by Gao Qiang et al. [27], studies on multi-sensor fusion SLAM are summarized: multiple low-cost sensors can be deployed to collect high-value environmental data. The theories and frameworks of visual-IMU fusion SLAM and visual-LiDAR SLAM deliver innovative directions for follow-up research.

2.3. Visual odometry and multi-sensor fusion

Odometry is the core factor directly determining the overall performance of SLAM technology. Visual odometry can be classified into supervised learning-based visual odometry and unsupervised learning-based visual odometry according to whether deep learning supervision is adopted. After systematic sorting by Chen Mingfang et al. [28], it is concluded that supervised learning SLAM algorithms have drawbacks in data dependence, generalization ability, real-time performance and applicable limitations, while unsupervised learning methods are restricted in positioning accuracy, data requirement threshold, training time and practical application foundations. It can thus be seen that visual odometry alone cannot support mobile robots to complete certain tasks fully. Therefore, the fusion of visual odometry and multiple sensors provides stronger guarantees for the navigation and localization of mobile robots. Yuan Zikang [29] pointed out that fusing data collected from different types of sensors can boost the accuracy and robustness of odometry. He further studied fusion strategies and practical application modes of the two technologies. The highlight of his research lies in the two types of depth-enhanced sensors adopted, namely depth cameras and LiDARs. With logically coherent elaboration across chapters, he illustrated the complete process of solving pose estimation problems through data fusion of visual sensors and depth-enhanced sensors. Lü Junzhong [30] focused on the localization demands of hexapod robots. He investigated methods to construct odometry for pose estimation using robot-borne sensors, and adopted multi-sensor fusion localization and data integration to acquire pose information with higher precision from visual odometry of robots. Zhang L et al. [31] proposed a multi-sensor fusion factor graph localization method integrating inertial measurement units, wheel odometers and LiDAR sensors. Combining the characteristics of multiple sensors and factor graphs, the researchers constructed a localization model named MSF-FG. This model drastically cuts average positioning errors while lowering computational complexity, and greatly enhances the stability of the whole system. Luo L et al. [32] put forward a dynamic odometry algorithm called FAST-LIVO built upon a high-speed LiDAR-Inertial-Visual Odometry system to tackle dynamic localization challenges. The algorithm achieves continuous, reliable and high-precision pose estimation in complex dynamic environments. Huang G et al. [33] designed a multi-sensor fusion method embedded within the Wheel-Inertial Visual Odometry (WIVO) framework based on Fuzzy Inference System (FIS). A fusion filter combining FIS and Improved Error State Kalman Filter (IESKF) is used to optimize rule parameters, which effectively suppresses odometry drift of mobile robots and improves localization accuracy and system robustness during dynamic movement. Liu C et al. [34] developed an embedded high-precision multi-sensor fusion system consisting of a multi-frequency multi-constellation GNSS module, consumer-grade inertial measurement unit (IMU) and grayscale camera. A Multi-State Constraint Kalman Filter is applied to generate tightly coupled estimation results from camera and IMU data, which remarkably improves the accuracy and continuity of independent GNSS positioning. Fu S et al. [35] presented an extended multi-sensor fusion localization system named MFL-SLAM, which directly integrates wheel odometry and visual-inertial SLAM into the ORB-SLAM3 framework. Innovatively, this system effectively compensates inertial bias and wheel slippage generated during rotational motion, delivering a reliable localization solution for indoor mobile robots.

2.4. Emerging algorithms and technologies

With continuous technological advancement, mobile robot techniques are iteratively updated and upgraded. A series of novel algorithms and technologies have been derived on the basis of mature

sensor and SLAM technologies. Li Rendong [36] carried out research on localization and navigation algorithms for mobile robots with depth cameras, taking advantage of stable data acquisition, low computing load and steady position solving performance, and put forward new research ideas for relevant fields. Dong Lin [37] studied intelligent optimization algorithms for mobile robots to optimize the performance of swarm intelligence optimization algorithms and offer new approaches to indoor localization and path planning problems. She summarized the characteristics of the bilateral two-way ranging algorithm and trilateration localization algorithm, and reviewed grey wolf optimization algorithms applied in positioning tasks. Based on traditional ROS indoor navigation robots, Xie Ziheng [38] combined WiFi location fingerprinting and Bluetooth 5.1 positioning to generate more precise positioning data for robot navigation, making the system more suitable for intelligent logistics sorting warehouses. Zheng Rui et al. [39] proposed a millimeter wave navigation scheme. Leveraging the strong penetration capacity and high resolution of millimeter wave sensors, the scheme improves navigation accuracy and realizes fully autonomous robot navigation. The SVD-based non-iterative localization algorithm proposed by Zhang et al. [40] runs faster than traditional iterative Levenberg–Marquardt algorithms. It achieves highly stable and rapid three-dimensional positioning with centimeter-level positioning accuracy. Wong C C et al. [41] designed a multi-sensor fusion technology combining Deep Reinforcement Learning (DRL) and Multiple Model Adaptive Estimation (MMAE). Multiple experiments were conducted adopting LiDAR-based Point-to-Line Iterative Closest Point (PLICP), RGB-D camera-based ORB-SLAM2, residual anomaly detection, Proximal Policy Optimization (PPO)-based DRL model and Gazebo simulator. The technology successfully fuses multi-source sensor information and attains higher positioning precision. To fuse outdoor global navigation satellite system data, wheel odometry data, indoor two-dimensional LiDAR and odometry data together, Zhu Y et al. [42] proposed a zone topological set method. Precise positioning results are determined by acquiring feasible sets of updated zones and states, so as to estimate the position and state of mobile robots. Lin H Y et al. [43] presented a drift-free visual SLAM technology for mobile robot localization. By introducing global constraints to eliminate accumulated local errors, the technology mitigates positioning accuracy deviation caused by insufficient image feature points. Zhao J et al. [44] proposed an enhanced mapping algorithm based on Cyber-Physical Systems (CPS). A Kalman filter is integrated to realize multi-sensor data fusion, while the A* algorithm is combined with pure pursuit autonomous navigation algorithm to strengthen localization and mapping performance in complex indoor environments.

3. Applications of navigation and localization for autonomous mobile robots

After years of development, mobile robots equipped with mature navigation and localization technologies have been widely deployed in real-life scenarios. Navigation and localization serve as the core driving force that transforms mobile robots from rigid equipment executing simple repetitive tasks into intelligent agents capable of handling diversified complex missions. Autonomous mobile robots fall into three major categories, namely warehouse robots, unmanned aerial vehicles (UAVs), and service robots. This section systematically reviews the practical applications of navigation and localization technologies adopted by each type of mobile robot respectively.

3.1. Implementation of navigation technology in intelligent warehouse robots

The optimization of operational efficiency within the logistics industry heavily relies on warehouse robots. Geng Bin [45] stated that warehouse robots can boost working efficiency, cut labor costs and

streamline management workflows. Adopting patent analysis, he investigated the technical characteristics of patents covering five mainstream navigation and localization solutions for warehouse mobile robots: wireless positioning technology, Simultaneous Localization and Mapping (SLAM), magnetic navigation, landmark-based positioning, and multi-sensor fusion technology. Liu Yuheng [46] pointed out that a well-designed navigation system can reduce multiple types of costs for warehouse robots, including time consumption, mechanical wear and energy expenditure, and carried out in-depth relevant research. First, he explored SLAM for warehouse robots from the perspectives of environmental map classification, grid mapping principles, Gmapping algorithm fundamentals and map preprocessing. Next, he studied robot localization based on particle filter positioning algorithms and optimized adaptive Monte Carlo localization. Afterwards, he analyzed path planning methods by comparing traditional algorithms and improved variants. Finally, he constructed a hardware and software experimental platform to conduct navigation tests, which verified the effectiveness and feasibility of the integrated system. Navigation technologies have diverse extended applications in warehouse robots, all of which optimize and enrich the functionality and practicality of such robots from different dimensions. Zou Chu et al. [47] summarized representative research outcomes as follows. Ahmed [48] designed a collision avoidance system based on multi-core fuzzy logic and FPGA boards to enhance navigation safety and reduce mechanical abrasion of warehouse robots. Pradyumna R et al. [49] developed humanoid robots equipped with inertial measurement units and LiDAR for autonomous navigation, improving task execution precision. Manglani et al. [50] proposed a navigation system combining visual technology and path planning algorithms to support real-time navigation and obstacle avoidance. Gu M et al. [51] created an augmented reality system that elevates human-robot interaction safety and operational efficiency, effectively guaranteeing reliable running of warehouse robots. Qiu Z et al. [52] addressed multi-robot task allocation and path planning problems in intelligent warehouse systems. To minimize total task completion time, they proposed a Lagrangian relaxation heuristic algorithm with customized efficient strategies. Experimental results proved that the proposed algorithm outperforms baseline approaches and improves the overall throughput of intelligent warehousing systems. To resolve the limitation that conventional multi-robot path planning algorithms fail to meet practical operational demands, Shen G C et al. [53] put forward the Speculative Path Conflict Search (SPC) algorithm. This algorithm conducts collision detection during path searching to eliminate inter-robot collisions during operation, offering a new research direction for multi-robot path planning in warehousing scenarios. All the above achievements demonstrate the wide application and vital significance of navigation systems for warehouse robots.

3.2. Localization technology and flight path planning for unmanned aerial vehicles

Stable and accurate flight of unmanned aerial vehicles entirely depends on navigation and localization technologies. UAVs integrated with such technologies can perform topographic surveying and precise cargo delivery under human supervision, while reasonable flight path planning determines the efficiency and safety of UAV operations. Yu Feipeng et al. [54] noted that complex, variable and uncertain terrain in practical use degrades positioning performance when UAVs only adopt a single sensor. Accordingly, they proposed a multi-sensor localization method. Their research adopted pyramid Lucas-Kanade optical flow aided by IMU prior information, performed tightly coupled nonlinear optimization on IMU data, and fused all sensor measurements via an error-state Kalman filter. The integrated framework effectively improves real-time localization performance and enhances the UAV's adaptability to complicated environments. Regarding UAV inspection missions, Zhang Li et al. [55] conducted research on automatic

inspection and positioning technologies. They divided machine vision technology into six core modules: image acquisition and preprocessing, feature extraction, object detection and recognition, target tracking, image segmentation and three-dimensional reconstruction. Visual localization algorithms, GPS-visual fusion positioning, real-time path planning and obstacle avoidance were integrated into inspection positioning frameworks, yielding nodes with outstanding positioning capability. In terms of UAV flight path planning, Hou Yanli et al. [56] indicated that the classic Exponential Triangular Optimization (ETO) algorithm [57] suffers insufficient search capability, premature convergence to local optima and unstable performance. Their research adopted Beta distribution strategies alongside bidirectional learning and evaluation mechanisms, proposing an improved ETO algorithm more suitable for UAV path planning. The complete research workflow included model establishment, algorithm optimization and simulation verification. Liu Hongqi et al. [58] summarized that path planning consists of two core phases: environment modeling and constraint formulation, and reviewed mainstream algorithms such as A*, genetic algorithm and particle swarm optimization, providing references for follow-up path planning research. Liu H et al. [59] proposed a novel autonomous path planning algorithm named APPATT based on tangent intersection points and target-guided strategies to generate collision-free high-quality flight paths for UAVs. The algorithm adopts an elliptical tangent graph method to produce two alternative subpaths, selects feasible routes through heuristic rules when obstacles are encountered, and iteratively adjusts trajectories to derive collision-free paths, enabling the UAV to escape simple obstacle traps within acceptable computation time. For indoor UAV navigation, Lin H Y et al. [60] combined RTAB-map SLAM indoor mapping with ROS-based indoor path planning. The joint global and local planner circumvents all types of static, dynamic, known and unknown obstacles and achieves high-precision indoor positioning. Yang X et al. [61] presented an integrated inertial navigation and GPS positioning framework for collaborative intersecting path planning of UAV swarms to tackle environmental challenges in complex low-altitude airspace. The method constructs environmental models, analyzes dynamic flight characteristics, and updates system states via inertial-GPS fusion positioning, exhibiting prominent advantages in cooperative cross-path planning for UAV clusters. Xiong H et al. [62] targeted the bottlenecks of traditional UAV navigation control, namely heavy reliance on ground control stations, limited onboard computing power and communication latency. They first designed a cloud-UAV collaborative navigation planning architecture, then developed corresponding background cloud navigation planning algorithms and terminal-side UAV algorithms, which significantly boosts the efficiency of UAV navigation trajectory planning.

3.3. Autonomous localization and path planning technologies in service robots

The field of service robots covers a wide scope and can be subdivided into various specific types, such as floor sweeping robots, restaurant delivery robots and patrol robots. Hu Yating [63] classified service robots into professional service robots and household service robots by application purposes. She identified the defect of unstable continuous operation existing in indoor service robots and carried out in-depth targeted research. She investigated point-line feature processing based on RGB-D cameras and visual-inertial SLAM systems built upon point-line features, conducted experimental verification and analysis on the visual-inertial SLAM framework, and finally developed a complete visual-inertial SLAM system that improves the market competitiveness of indoor service robots in the consumer sector. Yin Huajun [64] argued that against the backdrop of deepening population aging nationwide, indoor service robots play a vital role in easing the imbalance between social labor supply and demand. He adopted multi-sensor fusion, SLAM technology and control theory to realize intelligent operation and harmonious human-robot interaction. For autonomous localization,

he started from functional requirements of navigation systems to design hardware architecture and software programs, analyzed the principles of dead reckoning and LiDAR positioning, and formulated a localization scheme suitable for semi-structured environments. In terms of path planning, he completed modeling and analysis of indoor environmental maps, optimized the particle swarm optimization algorithm, and constructed a genetic particle swarm algorithm. Wang Gang et al. [65] held that autonomous navigation and localization constitute the top priority to be solved for service robots and serve as an indicator of robot intelligence. They researched trajectory performance of the Hector SLAM algorithm, unscented Kalman filter and adaptive unscented Kalman filter, and identified effective approaches to boost localization accuracy via simulation tests. In the field of path planning, Pan Zheng [66] pointed out that service robots need to be optimized for stable operation in complex environments and rapid target arrival while avoiding obstacles. In his research, he took the `move_base` package under the ROS platform as the foundation of path planning algorithms, then studied a multi-path simultaneous search TEB algorithm and a dynamic obstacle avoidance strategy to realize evasion of moving barriers. Chen C H et al. [67] designed a cloud-based conversational navigation agent system for campus service robots. Its core functions include interactive dialogue services, real-time path planning and route guidance, featuring strong interactivity and practical usability. After analyzing mainstream indoor localization methods and ultrasonic positioning technologies widely adopted at present, Wang G et al. [68] developed a dedicated system for mobile household service robots, whose positioning accuracy and path planning practicability were verified through experiments. Trulls E et al. [69] proposed a fully autonomous navigation solution applicable to urban pedestrian environments. Taking robot kinematic characteristics into consideration, the scheme adopts a three-dimensional map-based particle filter for localization and surface traversability inference for low-level navigation. It adapts to terrain elevation variations and has been tested in diverse urban scenarios, proving its high task completion success rate. Yu Q et al. [70] developed a customer service robot for catering scenarios. The robot adopts segmented localization and shape-based matching tracking methods, and the proposed pose estimation algorithm outputs real-time coordinate data, which enhances the robot's ability to reach target objects and improves the precision of object grasping.

4. Challenges and future development trends

Since the development of navigation and localization technologies for mobile robots, remarkable breakthroughs have been achieved alongside multiple challenges. These challenges arise from hardware and algorithm layers collectively, forming key research directions that require further improvement in this field. This section summarizes existing challenges in mobile robot navigation and localization, and discusses prospective development trends.

4.1. Current technical challenges

Challenges in this research field are diverse. Despite continuous advances in algorithms, hardware technologies and practical applications, inherent drawbacks remain unresolved. From the perspective of sensor-based localization, individual sensors have inherent limitations: positioning accuracy is vulnerable to environmental interference, a balance between cost and operational efficiency is hard to achieve, and the acquired environmental information lacks comprehensiveness. As for SLAM technologies, LiDAR SLAM delivers high positioning accuracy yet suffers high hardware costs and sparse environmental data. Visual SLAM features low cost and rich visual information, but its performance degrades drastically under extreme illumination or unstructured

surroundings. Although multi-sensor fusion can complement the strengths of separate sensors and optimize overall performance, it still poses challenges including high development difficulty, intricate algorithm logic and elevated deployment costs. Supervised learning visual odometry is highly reliant on training datasets and exhibits weak generalization capacity. Unsupervised learning visual odometry is restricted by insufficient positioning accuracy and lengthy training cycles. Neither type can independently complete high-precision pose estimation tasks, and their fusion with multi-sensor systems faces obstacles in data alignment and fusion strategy formulation.

Though emerging algorithms show favorable performance in specific scenarios, most are still in experimental verification stages. Further breakthroughs are required to improve their practicability, real-time responsiveness, general applicability and deep integration with existing robotic systems. In practical deployment scenarios, long-hour continuous operation of warehouse robot navigation systems calls for further reduction of mechanical abrasion and energy consumption. For unmanned aerial vehicles, single-sensor positioning accuracy declines drastically on complex and volatile terrain, and the search efficiency and real-time obstacle avoidance capacity of path planning algorithms need enhancement. Service robots lack stable long-duration operation capability in indoor environments, and autonomous obstacle avoidance plus rapid path decision-making under complicated conditions remain prominent technical bottlenecks.

4.2. Directions for future technical innovation

The aforementioned defects and challenges of navigation and localization technologies for autonomous mobile robots are exactly the core innovation orientations for future research. Subsequent studies shall focus on improving cross-scenario adaptability, upgrading multi-sensor fusion frameworks toward low cost and high efficiency to realize high-precision data acquisition and reduce measurement errors. Meanwhile, path planning algorithms should be optimized for higher computational efficiency and real-time performance to adapt to various complex operating environments. Researchers are also encouraged to integrate emerging technologies to diversify experimental schemes and facilitate technological innovation.

The integration of artificial intelligence with mobile robot navigation and localization represents the core developmental trend in the future. Intelligent optimization algorithms and deep learning models can be embedded into localization and path planning modules to support real-time positioning and autonomous decision-making in dynamic environments, enabling instantaneous obstacle avoidance. Furthermore, artificial intelligence can be combined with multi-sensor systems to intelligently fuse and precisely analyze collected environmental data, so as to adapt to complex, changeable and unstructured scenarios and accelerate the intelligent upgrading of mobile robots into fully autonomous mobile robots.

5. Conclusion

This paper conducts a systematic comprehensive review of navigation and localization technologies for mobile robots. It sorts out the research background and prevailing technical problems, identifies core optimization targets covering algorithm design, sensor hardware and positioning accuracy, and elaborates mainstream research approaches including algorithm design, simulation verification and experimental optimization. This paper mainly summarizes research progress and technical characteristics of four major categories of navigation and localization methods: sensor-based localization, SLAM, visual odometry with multi-sensor fusion, and emerging intelligent algorithms. It also analyzes practical deployment cases and adaptive technical strategies in three typical

application scenarios, namely warehouse robots, unmanned aerial vehicles and service robots. In addition, this paper dissects core existing challenges in sensor integration, SLAM performance and path planning efficiency, and explores technological innovation paths as well as the integration trend with artificial intelligence. The systematic collation in this paper provides comprehensive references for follow-up research on mobile robot navigation and localization, points out research directions for technical optimization and scenario-based industrial implementation, and promotes the development of such technologies toward high precision, full intelligence and low deployment cost.

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