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Applications and Prospects of SLAM Technology in Mobile Robot Design

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Abstract. This paper studies the application of simultaneous localization and mapping (SLAM) technology in the design of mobile robots. Traditional SLAM research lacks a systematic approach and adaptability to actual work tasks, making it difficult for researchers to choose reasonable architectures for optimized design, thereby limiting the further development of SLAM technology. The paper begins by introducing the definition and development history of SLAM technology, then introduces six kinds of SLAM technologies in the application framework of mobile robots, comparing and analyzing their applicable scenes based on each technology's characteristics. It proceeds to analyze typical applications of mobile robots with SLAM technology in Autonomous Mobile Robots and three-dimensional (3D) environment exploration, as well as search and rescue operations, rounding off with an analysis and summary of prospects of SLAM technology in mobile robot design. This study offers targeted solutions by employing listing and comparison methods combined with practical application analysis, thus better-assisting researchers in choosing reasonable architectures for optimization. This paper facilitates researchers in choosing reasonable architectures for designing mobile robots under different scenarios. In conclusion, it proposes prospects of SLAM technology in mobile robot design, providing direction for research on SLAM technology in mobile robots.

Keywords: SLAM; Mobile robot; Rescue; 3D.

1. Introduction

SLAM technology has been widely applied in the field of mobile robotics, becoming a key technology for realizing robot autonomous navigation and environment understanding [1-2]. Currently, the SLAM technology used by mobile robots includes those based on laser imaging, detection, and ranging (LiDAR), visual SLAM (VSLAM), or a combination of both in multi-sensor fusion SLAM systems. With the improvement of computing power and the integration of deep learning methods, modern SLAM systems can provide higher accuracy, stronger robustness, and faster processing speeds. The utilization of deep learning, such as feature extraction and environmental understanding through convolutional neural networks, has greatly advanced the performance of SLAM. Additionally, contributions from open-source projects and communities, such as Google's Cartographer [3-4], have also fostered the spread and innovation of technology, enabling SLAM technology to continuously adapt to a wider range of application scenarios, including intelligent robotics, autonomous driving systems, augmented reality, and virtual reality, among others. Overall, SLAM technology is in a rapid development stage, with new algorithms and applications emerging constantly, but there are also some challenges and issues that need to be resolved:

Balancing accuracy and real-time performance: Some SLAM algorithms may sacrifice a certain level of accuracy in pursuit of real-time performance, while applications requiring high precision may need more complex algorithms. Finding a balance between accuracy and real-time performance is an important issue.

Long-term stability: Some SLAM systems may experience cumulative error issues after running for an extended period, leading to map drift or inaccurate localization. Achieving long-term stability is a challenge that needs to be addressed.

Adaptability to Dynamic Environments: The presence of dynamic objects can disrupt SLAM systems, especially in applications requiring real-time map updates. Effectively identifying and handling dynamic objects is an important issue.

Sensor Fusion: Modern SLAM systems typically need to integrate data from multiple sensors such as LiDAR, cameras, and inertial sensors to enhance localization and map construction accuracy. Effectively fusing data from different sensors is a technical challenge.

Applications in Large-Scale Environments: Some SLAM algorithms perform well in small-scale environments but may face performance degradation in large-scale environments. Adapting algorithms to suit larger environments is a challenge that needs to be addressed.

The purpose of this paper is to help researchers choose reasonable architectures for optimization among the many SLAM algorithms in the design of mobile robots by summarizing the characteristics of various SLAM algorithms and analyzing their applicable scenarios by listing two typical applications of mobile robots based on SLAM technology.

The first part of the paper introduces SLAM technology, including an overview and a brief history of its development. The second part analyzes the application frameworks of SLAM technology in mobile robots using a listing method, introducing six types of SLAM technologies –Cartographer [3-4], Karto [5-6], LIO-SAM [7], LOAM [8], ORB-SLAM3 [9], VINS-Fusion [10] – and comparing their characteristics, advantages, disadvantages, and applicable scenarios in conjunction with Table 1. The third part analyzes two typical applications of mobile robots based on SLAM technology: (1) SLAM for autonomous mobile robots and 3D environment exploration [11], and (2) Search and Rescue Operations [12], linking SLAM theoretical knowledge with real situations. This analysis makes the theory more specific and easier to understand by applying it in specific contexts.

This paper can assist researchers in rationally selecting SLAM algorithms for mobile robots in different scenarios, and predicting the prospects of SLAM technology's application in the field of mobile robotics.

2. Introduction of SLAM Technology

2.1. SLAM Technical Overview

SLAM technology is an advanced technology that enables robots to explore and map their environment while simultaneously localizing themselves, even in the absence of external positioning systems such as global navigation satellite systems (GNSS) and global positioning systems (GPS).

The core of SLAM technology relies on various sensors carried by the robot, such as cameras, LiDAR, and inertial measurement unit (IMU). The data collected from these sensors are used to create a real-time map of the surrounding environment and to localize the robot within that map. The processing of sensor data is divided into two main parts: the front-end and the back-end. The front-end is responsible for processing sensor data, identifying features in the environment, and tracking them; the back-end, on the other hand, uses this data to estimate the robot's position and build the environmental map.

Challenges faced by SLAM technology include its effectiveness in dynamic environments, the integration of data from different sensors, and how to handle large amounts of data for real-time performance. Although IMU sensors are crucial for measuring linear and rotational accelerations of the robot, due to the accumulation of errors, they often need to be combined with other systems such as GNSS to enhance accuracy.

Recent advances in SLAM research include the use of deep learning technologies to improve feature detection and data association, as well as computational optimizations to enhance the efficiency and accuracy of back-end processing. These technological advancements have led to more precise and reliable SLAM solutions, thereby expanding its application in the real world.

Currently, SLAM technology is widely applied in autonomous vehicles, drones, automated industrial robots, and augmented reality and virtual reality, among other fields. As algorithms, hardware, and software continue to evolve, SLAM technology will play an increasingly important role in automation and robotics, enabling these systems to navigate and perform tasks safely and effectively without the need for pre-built maps [1].

2.2. A Brief History of SLAM Technology Development

Early development (Mid-1980s to 1990s):

This technology was first introduced at an international conference in 1986, and the term “SLAM” was formally proposed by Durrant-Whyte and others in 1995.

The concept of SLAM technology began to take shape in the mid to late 1980s, with researchers focusing on the problem of simultaneous localization and mapping in unknown environments.
In 1990, Hugh Durrant-Whyte and John Leonard first introduced the modern SLAM problem in their research. They, along with other research teams, began initial experiments with SLAM using radar and laser scanning sensors.
Exploration of algorithms and methods (1990s to Early 2000s):

During this period, researchers developed various SLAM algorithms, including the Extended Kalman Filter (EKF-SLAM), which mainly focused on effectively achieving localization accuracy and map stability.

The Vertex Tree Algorithm (Spa framework) and FastSLAM were also proposed during this time, each providing different solutions and perspectives on the SLAM problem.

The Rise of Visual SLAM (Mid-2000s to Present):

With the rapid development of computer vision technology, Visual SLAM (VSLAM) began to receive more attention. VSLAM uses cameras as the primary sensors, reducing system costs while increasing usability.

In 2007, Georg Klein and David Murray developed Parallel Tracking and Mapping (PTAM), marking a significant milestone for modern visual SLAM.

Subsequently, emerging VSLAM systems such as ORB-SLAM and LSD-SLAM appeared, significantly improving real-time performance, accuracy, and robustness.

Integration of Learning and Deep Learning (2010s to Present):

The rise of deep learning has further advanced SLAM technology. Researchers have begun to use convolutional neural networks (CNNs) and other deep learning models to enhance the SLAM system's feature extraction and environmental understanding capabilities.

Deep neural networks are used to solve different problems in SLAM, such as depth prediction, semantic segmentation, and tracking of dynamic objects in augmented reality.

Future Directions:

It is anticipated that future SLAM technology will further integrate various sensing technologies and artificial intelligence methods to enhance performance in dynamic and complex environments.

SLAM technology will play a more significant role in several fields, including autonomous driving, robotics, augmented reality, and virtual reality.

SLAM technology is a highly challenging problem within the field of artificial intelligence for mobile robots, with scientists using various techniques to improve autonomy and self-exploration capabilities over the past twenty years. As a key problem-solving approach, SLAM is suitable for scenarios where prior map knowledge is not available or existing maps are not desired. Simply put, SLAM involves building a map of the environment without any prior knowledge while ensuring that the robot can locate itself within this construction process without human intervention. Thus, SLAM technology provides robots with the ability to operate in environments lacking specific localization infrastructure.

As research has deepened and technology has advanced, SLAM technology has become indispensable for indoor and outdoor applications. Researchers have developed multiple SLAM solutions while continuously seeking more reliable and faster technologies to improve performance. The development goal of SLAM technology is to achieve fully autonomous navigation in any environment (such as indoor, outdoor, underwater, air, etc.) while maintaining the lowest possible estimation error, longer life, and the fastest mapping speed, considering the need for low power consumption, low computational cost operations, and simplicity.

Past research and reviews have primarily focused on specific aspects or technical approaches of SLAM, such as vision-based SLAM for keyframes, SLAM solutions under multi-robot cooperation, vision-based positioning methods, and SLAM algorithms for autonomous vehicles. However, these studies are often limited to specific applications or a certain class of technology within a certain period, lacking a comprehensive overview of the evolution of SLAM technology [2].

3. Application Frameworks of SLAM technology in Mobile Robots

3.1. Cartographer

Cartographer is an SLA method developed by Google, which incorporates grid-based mapping and a Ceres-based scan matching algorithm to reconstruct environments across various sensor configurations. Initially designed for portable applications to map unknown areas with an IMU and LiDAR carried in a backpack, Cartographer has since been made open source and is now managed by an open-source community. Through various improvements, its application scope has been broadened to include support for larger maps, more sensor integrations, and other technological advancements to support intelligent robots. As an effective SLAM technology, thanks to continuous innovation and improvements from its open-source community, Cartographer has become a powerful tool for enabling precise localization and map construction for intelligent robots and future autonomous driving systems in complex environments [3-4].

3.2. Karto

Karto SLAM is a graph-based optimization method primarily used for SLAM tasks. It effectively utilizes a highly optimized, non-iterative Cholesky matrix for sparse system decoupling, and the average of the graph represents the map, where each node corresponds to a location point in the robot's trajectory and the sensor dataset. As new nodes join, the map is recalculated and updated based on the constraints imposed by the node arrows in space.

One main advantage of this algorithm is its superior performance in large environments, though its computational complexity increases with the number of landmarks. Karto SLAM uses Spare Pose Adjustment (SPA) for scan matching and loop closure detection, implemented in its ROS version. The map quality exhibited in both real-time and simulation tests shows some errors, but the maps produced are very similar, with the simulation session generating slightly better-quality maps than the real-time session.

Karto SLAM is an effective SLAM algorithm, particularly notable for its fast-mapping capabilities and lower error rates. While it is slightly less accurate compared to some other SLAM algorithms, its performance is very similar to that of GMapping SLAM. Despite increasing computational complexity with more landmarks, Karto SLAM remains efficient under default settings, demonstrating its capability for rapid mapping [5-6].

3.3. LIO-SAM

The lidar inertial odometry via smoothing and mapping (LIO-SAM) is a framework designed for real-time accurate trajectory estimation and map building for mobile robots. It builds a lidar inertial odometry on top of a factor graph, capable of fusing different sources of relative and absolute measurement data, including loop closures, as factors of the system. Through pre-integration estimates from the IMU to correct point clouds and generate initial estimates of lidar odometry optimization. The resulting solution of lidar odometry is used to estimate IMU biases.

This framework efficiently enhances the capacity of sensor fusion through global optimization by integrating multi-sensor data in the factor graph. To ensure real-time performance, LIO-SAM adopts local scan matching instead of global map matching, with the introduction of keyframes and an efficient sliding window approach to improve the real-time performance of the system.

The main capabilities of LIO-SAM include:

(1) Proposing a tightly-coupled lidar inertial odometry framework based on a factor graph, suitable for multi-sensor fusion and global optimization.

(2) Introducing an efficient local scan matching method by selectively adding keyframes and using a fixed-size pre-front “sub-keyframe” set, achieving real-time performance.

(3) Validating the effectiveness of the framework through extensive testing under various scales, vehicles, and environments.

LIO-SAM is suitable for multi-sensor fusion, easily integrating new sensor measurements as new factors, including sensors providing absolute measurements (such as GPS, compass, or altimeters) to eliminate drift accumulated over time or in feature-poor environments. Moreover, this architecture also supports easy integration of location recognition. By local rather than global scan matching, and using a sliding window method to marginalize old lidar frames for scan matching, LIO-SAM enhances the system’s real-time performance.

Future work will include testing the system on drones to further verify its flexibility and applicability. Overall, LIO-SAM offers significant improvements in addressing drift issues often encountered in large-scale testing and provides high-precision real-time mobile robot trajectory estimation and map-building capability through its tightly coupled and global optimization scheme [7].

3.4. LOAM

Lidar odometry and mapping (LOAM) is a lightweight lidar SLAM system aimed at providing the public with a real-time, practical lidar SLAM solution. Its method combines feature extraction, distortion compensation, pose optimization, and mapping. Compared to traditional LOAM methods, it can also utilize a non-iterative two-stage distortion compensation method to replace the computationally inefficient iterative distortion compensation method. Additionally, it has been observed that edge features with higher local smoothness and planar features with lower smoothness tend to be consistently extracted in successive scans. These points are more important for matching, hence the local geometric feature is also considered in the iterative pose estimation to improve localization accuracy.

The system is capable of real-time operation on low-power embedded computing units, with performance reaching up to 20Hz. To demonstrate its robustness, a comprehensive evaluation of the proposed method was carried out, including both indoor and outdoor experiments. Compared to existing state-of-the-art methods, this method can achieve competitive localization accuracy at a lower computational cost, offering a good compromise between performance and speed. Notably, the proposed method is one of the most accurate and fastest open-source methods in the KITTI benchmark.

LOAM presents a new lidar SLAM framework with high computational efficiency and good localization accuracy, making it especially suitable for robotic application fields where real-time capability and limited computational resources are a concern, such as autonomous driving, drone inspection, and warehouse handling [8].

3.5. ORB-SLAM3

ORB-SLAM3 is an advanced visual and visual-inertial SLAM system capable of handling various sensor configurations, including monocular, stereo, and RGB-D cameras, equipped with pinhole or fisheye lens models. It builds on the previous version of ORB-SLAM, integrating several innovative features that significantly enhance its performance, stability, and accuracy across diverse environments and scenarios.

Key features of ORB-SLAM3:

Visual-Inertial Integration: ORB-SLAM3 introduces a robust visual-inertial SLAM system that seamlessly combines visual information with inertial measurements. This integration, from initialization to maximum a posteriori (MAP) estimation, notably improves the stability and accuracy of real-time operations compared to previous methods.

Multi-Map Capability: A distinguishing feature of ORB-SLAM3 is its ability to manage multiple maps simultaneously. This multi-map system integrates improved place recognition algorithms, enhancing recall capabilities, allowing the system to initiate new maps in visually deprived environments, and merge them with existing maps when revisiting previously mapped areas.

Information Reuse: Unlike traditional visual odometry systems, ORB-SLAM3 retains and utilizes all previous mapping information, including keyframes from past sessions with high disparity visibility. This capability significantly enhances accuracy by allowing the system to maintain awareness of the environment over longer time spans and distances.

ORB-SLAM Atlas: This component represents a comprehensive multi-map system that can seamlessly manage different maps. It supports the integration and interaction between different maps to effectively perform place recognition, camera relocalization, loop closure, and map merging. This feature makes incremental multi-session SLAM on a large scale possible.

Abstract Camera Representation: ORB-SLAM3 is designed to be agnostic of the camera models used, supported by an abstract camera representation. This allows easy integration of different camera models by defining specific projection, de-projection, and Jacobian functions, giving the system high adaptability.

Open Source Contribution: Continuing the tradition of ORB-SLAM, the source code of ORB-SLAM3 is publicly available, providing a valuable resource for the research community and practitioners in the field. This openness fosters further development and adaptation across various applications.

ORB-SLAM3 has been comprehensively evaluated on multiple public datasets, demonstrating its stability and high accuracy in different configurations, such as stereo-inertial and monocular-inertial setups. It performs particularly well in typical challenging scenarios encountered in drone navigation and AR/VR applications, where precise and reliable localization is crucial. Despite numerous improvements, ORB-SLAM3 still faces challenges in low-texture environments where direct methods might offer better robustness.

ORB-SLAM3 significantly pushes the boundaries of visual and visual-inertial SLAM capabilities, providing a robust, accurate, and versatile system suitable for a wide range of applications. However, ongoing improvements and adaptations, such as enhancements in handling low-texture environments and integrating new sensory technologies, will further enhance its utility and application scope [9].

3.6. VINS-Fusion

VINS-Fusion is an advanced vision-inertial SLAM system designed to enhance the accuracy and stability of positioning and map construction by integrating data from multiple sensors. It primarily utilizes vision and IMU data and can fuse with other sensors like LiDAR to achieve higher positioning accuracy and more detailed mapping. Here's a summary of the key features and applications of VINS-Fusion:

Key features:

Multi-Sensor fusion: VINS-Fusion integrates data from vision and inertial sensors and has the capability to fuse data from other sensors such as LiDAR, providing more accurate and stable positioning and mapping information.

Real-time positioning: The system can process data from various sensors in real-time, quickly and accurately updating position information in dynamic environments, which is especially important for fast-moving devices like drones and autonomous vehicles.

High-accuracy positioning: With the effective fusion of vision and inertial data, VINS-Fusion achieves high precision in positioning, meeting the high accuracy demands for applications such as autonomous driving and robotic navigation.

Open source platform: The source code of VINS-Fusion is open, allowing researchers and developers to customize and extend it to suit specific application requirements.

Applications:

Drone navigation: Provides stable and precise flight positioning and environment mapping, enhancing the autonomous flight capabilities of drones in complex environments.

Autonomous driving vehicles: Supports accurate vehicle positioning and environmental perception, a key component in the realization of autonomous driving technologies.

Augmented reality: Enhances the user experience in augmented reality applications through accurate position tracking and environmental understanding.

VINS-fusion, being a mature vision-inertial SLAM system, offers a robust tool foundation, supporting further research such as fusion with traditional SLAM techniques or innovative applications of deep learning methods, exploring more innovative application directions.

VINS-fusion is an advanced SLAM system with wide application potential in several critical areas. With its strong multi-sensor data fusion capability, it significantly improves positioning and map construction performance in dynamic environments, making it an indispensable technology in modern fields like drone navigation, autonomous driving, and augmented reality [10].

3.7. Technical Analysis and Discussion

Characteristics of several SLAM methods are shown in Table 1.

Table 1. Characteristics of several SLAM methods

SLAM method	Cartographer	Karto	LIO-SAM	LOAM	ORB-SLAM3	VINS-FUSION
Sensor	Based on 2D LiDAR	Based on 2D LiDAR, closely integrated with ROS	Based on 3D LiDAR	Based on 3D LiDAR. Good for slow-moving scenarios	Vision sensor-based	Based on vision and inertial sensors
Robustness	H	M	M	M	M	H
Positional accuracy	H	M	M	M	H	H
Mapping area	G	M	M	S	M	M
Mapping quality	H	H	H	H	M	H
Real-time performance	M	H	H	H	H	M
Scalability	M	M	M	L	M	H
Hardware requirements	H	H	M	H	L	H
Project implementation difficulty	M	L	H	L	H	H

Note: H - High, M - Moderate, L – Low, G – Large, S – Small.

3.7.1. Cartographer.

Advantages: High robustness, high positioning accuracy, and good mapping quality, suitable for large areas. Moderate real-time performance suggests it performs well in real-time applications but may not be the best.

Disadvantages: High hardware requirements, moderate scalability, and medium difficulty in engineering implementation make it potentially less ideal for situations with limited resources or where rapid deployment is needed.

Suitable Scenarios: Ideal for large-scale indoor and outdoor mapping and navigation, such as warehouse management, navigation in large office or commercial buildings, or even city-level map construction.

3.7.2. Karto.

Advantages: Closely integrated with ROS, easy to implement and extend within the ROS ecosystem. High mapping quality, good real-time performance, and easy engineering implementation.

Disadvantages: Medium robustness, positioning accuracy, and mapping area might perform poorly in complex environments or wide-range applications.

Suitable Scenarios: Extremely suitable for medium and small projects in education, research, and development, especially where rapid prototyping and development are needed.

3.7.3. LIO-SAM.

Advantages: Based on 3D LiDAR, provides high mapping quality and good real-time performance. Suitable for three-dimensional mapping and positioning.

Disadvantages: Moderate hardware requirements, but higher difficulty in engineering implementation, may need more professional knowledge and experience.

Suitable Scenarios: Suitable for applications requiring high-precision 3D mapping, such as navigation in complex industrial environments, interior design, and Building Information Modeling (BIM).

3.7.4. LOAM.

Advantages: Performs well in slow-moving scenarios, high mapping quality, and good real-time performance.

Disadvantages: High hardware requirements and poor scalability, limited positioning accuracy, and mapping area.

Suitable Scenarios: Suitable for precise indoor or small area 3D mapping at relatively constant speeds, such as indoor navigation, heritage conservation, and renovation projects.

3.7.5. ORB-SLAM3.

Advantages: Vision-based SLAM technology, low hardware requirements, high positioning accuracy, and good real-time performance.

Disadvantages: Medium mapping area, average mapping quality, and higher difficulty in engineering implementation.

Suitable Scenarios: Very suitable for resource-limited platforms such as handheld devices, drones, etc., can be used for indoor and outdoor navigation, augmented reality, etc.

3.7.6. VINS-FUSION.

Advantages: Fusion of vision and inertial sensors increases robustness and positioning accuracy, with high mapping quality. Moderate real-time performance, and high scalability.

Disadvantages: Higher hardware requirements, and higher difficulty in engineering implementation, may not be suitable for beginners or projects with limited resources.

Suitable Scenarios: Due to its high robustness and accuracy, it is particularly suitable for applications in fast-moving and dynamic environments, such as autonomous driving assistance systems, and mobile robotics navigation in complex environments.

When choosing SLAM technology, the specific requirements of the application scenario should be considered, including the size of the environment, its dynamism, hardware resources, and the complexity of engineering implementation. Different technologies have their advantages and are suitable for different application scenarios and tasks. Considering these factors during the selection process can help determine the SLAM technology that is best suited for a particular task.

4. Typical Applications of Mobile Robots Based on SLAM Technology

4.1. SLAM for Autonomous Mobile Robot and 3D Environment Exploration

Applications of Mobile Robots Based on SLAM Technology

Inspection in Dangerous and Isolated Terrains: SLAM technology enables mobile robots to navigate and map environments that are hazardous or unsuitable for human presence. This application is crucial for ensuring safety and efficiency in areas such as nuclear facilities, chemical plants, and other dangerous sites where human intervention is risky.

Service Tasks in Public Multi-Level Buildings: Mobile robots equipped with SLAM can perform various service tasks in complex building environments like hotels, hospitals, and warehouses. These tasks may include delivery of goods, guiding visitors, patient assistance, and surveillance, all requiring navigation between different levels of the building.

Precise Pose Tracking and 3D Mapping: Using laser rangefinders and inertial navigation systems in conjunction with SLAM allows robots to maintain precise tracking of their location while generating a real-time 3D map of the environment. This capability is vital for tasks that require high accuracy in positioning and detailed environmental awareness, such as construction and maintenance in intricate architectural settings.

Path Planning and Motion Planning: SLAM technology assists in both path planning and reactive motion planning by providing accurate maps and real-time localization. This feature is essential in environments where conditions can change unpredictably, requiring the robot to adapt its path dynamically to avoid obstacles and efficiently reach its target.

Implementation in Robot Operating Systems: The integration of SLAM within robotic operation systems (such as ROS) facilitates its use in real-world applications. This integration supports various functionalities in mobile robotics, enhancing the robot's ability to perform its tasks autonomously while adapting to new environments swiftly.

These applications demonstrate the versatility and critical importance of SLAM technology in enhancing the capabilities of mobile robots, particularly in scenarios where precision, safety, and adaptability are paramount [11].

4.2. Search and Rescue Operations

4.2.1. Urban Search and Rescue Missions Utilizing Monocular SLAM Integrated with 2D LiDAR Technology.

Urban search and rescue (USAR) operations can employ a monocular SLAM system, enriched with an object recognition module tailored for ground mobile robots in USAR tasks. This system harnesses the simplicity and cost-effectiveness of monocular SLAM, augmenting it by integrating it with 2D LiDAR SLAM to overcome its inherent limitations. This hybrid approach not only facilitates a better understanding of mapping by operators but also enhances the robots' localization accuracy in complex environments like stairs and ramps. Demonstrated in real-world USAR simulations, the system has shown great potential and received acknowledgment in international competitions.

USAR tasks necessitate autonomous systems capable of navigating and mapping in highly unstructured environments. Due to cost considerations and equipment simplicity, SLAM technology often favors monocular systems. Although economically advantageous, these systems typically face challenges in in-depth perception and feature tracking, crucial in chaotic disaster scenes. This paper proposes a unique integration of monocular SLAM with 2D LiDAR technology, maintaining the strengths of both systems while aiming to surmount such challenges.

4.2.2. Monocular SLAM Challenges in USAR.

Monocular SLAM, benefiting from its simplicity and cost-effectiveness, often encounters problems in USAR scenarios due to poor depth accuracy and unstable feature tracking in dynamic settings. These limitations commonly lead to navigation failures in uneven terrains such as debris, stairs, and ramps.

4.2.3. Integrating Monocular SLAM with 2D LiDAR.

This solution integrates detailed feature-based mapping and 6D localization offered by monocular SLAM with stable terrain mapping and real-scale environmental awareness provided by 2D LiDAR SLAM. This integration significantly enhances the robot's capability to maintain accurate navigation and mapping support across various challenging terrains typically encountered in USAR missions.

(1) System Implementation and Testing: The system has undergone rigorous testing in both simulated disaster environments and real USAR contexts, including participation in the RoboCup Rescue Robot League. These implementations have emphasized the system's robustness and enhanced user comprehension of the mapped environment. Utilizing this SLAM system has led to high placements in international competitions, validating its effectiveness and potential for application.

(2) Enhancements and Future Work: Despite its successes, the current system comprises somewhat separate applications of the two SLAM technologies. Future efforts aim to integrate these

technologies more seamlessly to further enhance operational efficiency and map readability. Additional improvements will focus on increasing the robots' autonomous capabilities, striving for a system capable of executing complex rescue tasks with minimal human intervention.

This paper introduces an innovative approach in USAR operations by applying monocular SLAM, innovatively combined with 2D LiDAR technologies. This hybrid system significantly improves the practical deployment capabilities of mobile robots in disaster scenarios, offering more comprehensible map outputs and enhanced navigational abilities. Ongoing development and integration efforts are expected to boost performance and autonomy, further enhancing the effectiveness of robots in USAR tasks [12].

5. Conclusion

This paper, through the comparison and enumeration of the characteristics of various SLAM algorithms, as well as analysis of multiple typical applications of mobile robots based on SLAM technology, concludes that:

Each SLAM technology has distinct characteristics making it suitable for specific tasks and environments. The choice of a specific SLAM algorithm depends on several factors, including the complexity of the environment, resource availability, the specific requirements for accuracy and real-time performance, and the technical challenges involved in implementing and maintaining the system. It is crucial to select the SLAM algorithm based on the actual scenario and the features of various algorithms. This paper summarizes some of the application scenarios suited for certain algorithms and the advantages and disadvantages of each feature, aiming to aid researchers in selecting from the multitude of SLAM algorithms. The analysis conducted in this paper on the applications of mobile robots based on SLAM technology involves a limited number of samples, with plans for expanding the sample size for further research in future studies.

Prospects of SLAM technology in mobile robot design:

SLAM technology has a broad and promising future in the field of mobile robot design, not only addressing the core challenges of autonomous navigation and environmental understanding but also continuously pushing the boundaries of robotic technology.

Technological integration and innovation: With the further integration of SLAM technology with deep learning and artificial intelligence, future SLAM systems will become more intelligent and adaptive. For instance, the enhanced feature recognition ability powered by deep learning will enable robots to identify and react to environmental changes more precisely.

Multi-sensor integration: Future SLAM systems will increasingly adopt multi-sensor fusion technology, combining LIDAR, visual SLAM, and other sensors to improve system accuracy and robustness. This will allow robots to perform better in a wider variety of complex environments.

Cost-effectiveness optimization: As the technology matures and is applied on a large scale, the costs of related hardware and software are reduced, making SLAM technology more accessible. This enables not only small and medium-sized enterprises but also ordinary consumers to utilize this technology for a wide range of daily applications.

Expansion of application range: From industrial automation to consumer products, and from indoor navigation to exploring complex outdoor environments, SLAM technology is gradually penetrating every corner of life. In the future, its application will not be limited to traditional fields. Instead, more emerging industries, such as public safety and healthcare, will be deeply developed.

Enhanced ability to adapt to the environment: Advances in SLAM technology will enable robots to better cope with dynamic changes in the environment, such as real-time map updates and long-term map maintenance, as well as enhancing decision-making and understanding of the environment through semantic information.

Collaboration and swarm intelligence: The future of SLAM could extend beyond individual robot capabilities to the collaboration and information sharing among a network of robots. By establishing a robot network, multiple robot systems could jointly complete more complex tasks, such as wide-area search and rescue operations.

Customization and flexibility of solutions: With the advancement of technology, customizing SLAM solutions for specific applications or environments will become easier and more efficient, meeting the specific needs of different users.

So, the continuous deepening and widening of SLAM technology in mobile robot design not only advances robotic technology but also brings about potential revolutionary changes to lifestyles. With ongoing technological progress and the expansion of application fields, a more intelligent and autonomous era of robots will come.

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