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Review on SLAM of Mobile Robot for Processing Inspection Based on Multi-Sensor Fusion

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ABSTRACT

With the rapid advancement of Industry 4.0 and smart manufacturing, traditional fixed processing and inspection equipment can no longer meet the flexible manufacturing demands of large-scale and complex-shaped components. Mobile processing and inspection robots, with their high adaptability and efficiency, have become critical equipment in modern workshops. This paper focuses on analyzing two mainstream solutions—visual-inertial fusion (VI-SLAM) and laser-visual fusion—emphasizing the advantages of multi-sensor fusion in enhancing robustness and precision. It provides a detailed exploration of the visual SLAM framework and algorithmic advancements based on feature points and deep learning. Additionally, the study investigates the collaborative design of global path planning and local obstacle avoidance algorithms, aiming to offer technical references for reliable autonomous navigation of mobile robots to preset workpoints in known environments.

KEYWORDS

Multi-sensor Fusion; SLAM; Machining Inspection; Mobile Robot; ROS; Path Planning.

1. INTRODUCTION

With the advancement of intelligent manufacturing, industrial workshop environments have become increasingly complex and dynamic. While traditional fixed-base machining systems offer high precision, their limited workspace makes them inadequate for manufacturing large-scale components. In response, mobile machining and inspection robots have emerged as essential equipment for producing and inspecting large components (such as aircraft engine blades), thanks to their flexible operation and expansive workspace.

However, the core challenge for mobile robots lies in their autonomous positioning and environmental perception capabilities. The workshop environment is filled with dynamic elements (such as personnel and material movement) and complex geometric features (like highly reflective metal surfaces), making it difficult for single sensors (e.g., relying solely on LiDAR or cameras) to achieve reliable map building and path planning in such environments. To address this, multi-sensor fusion SLAM technology has emerged. By integrating heterogeneous data from LiDAR, visual sensors (e.g., RGB-D cameras), and inertial measurement units (IMUs) [1], this technology significantly enhances system robustness and positioning accuracy, providing a solid perceptual foundation for high-precision machining operations by mobile robots .

2. BASIC CONCEPTS AND PRINCIPLES OF SLAM TECHNOLOGY

SLAM (Simultaneous Localization and Mapping) is a pivotal technology enabling autonomous navigation for mobile robots, allowing them to simultaneously determine their position and construct environmental maps in unknown environments without relying on prior maps or initial position data. A complete SLAM system typically comprises core modules such as state estimation, map building, and data association, which work collaboratively while facing technical challenges including nonlinear optimization, dynamic interference, and real-time performance. Based on the core sensors used, SLAM can be categorized into different technical approaches like laser SLAM and visual SLAM. Among these, visual SLAM, which primarily uses cameras as sensing sensors, has become the mainstream direction in SLAM research and applications due to its cost-effectiveness, rich information dimensions, and broad applicability. By extracting environmental features from visual images, it enables robot pose estimation and sparse/dense map construction. The following section will provide detailed introductions to two typical visual SLAM algorithms.

2.1. Visual SLAM Framework

Typically, a visual SLAM framework comprises several key components: sensor data acquisition, front-end processing, back-end computation, map construction, and closed-loop detection. In visual SLAM, sensor data acquisition involves capturing and preprocessing camera images. For multi-sensor fusion SLAM, it also requires data acquisition from inertial measurement units, LiDAR, and wheel encoders, along with synchronization across different sensors. The front-end, known as visual odometry (VO), processes input images from the preceding stage to estimate the camera's position and attitude at different time points. It also determines camera movements between adjacent images to acquire local map information. The back-end, referred to as nonlinear optimization, receives camera pose parameters from VO at different time points and performs optimization. Additionally, it processes closed-loop detection data to execute global optimization, ensuring consistent trajectory and map. The closed-loop detection thread verifies whether the mobile robot has revisited previously accessed locations; if confirmed, it establishes a closed loop and relays the information to the back-end for further processing. Finally, the map construction thread generates a complete global map based on the estimated camera trajectories from earlier stages and local maps from different time points. The visual SLAM framework is illustrated in Figure 1.

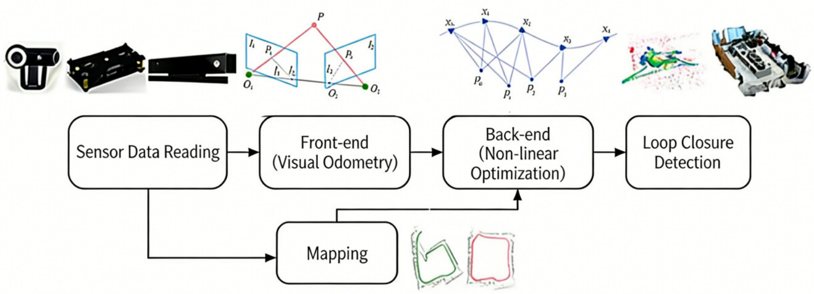


Figure 1. Visual SLAM Framework

2.2. Feature Point-Based Visual SLAM

Visual SLAM based on feature point method utilizes camera-collected image data to extract feature points, which are then used for pose estimation between camera frames. In this approach, cameras continuously capture scene features such as corners, edges, and textures during motion, which are employed to reconstruct camera poses and build scene maps. In 2007, DAVISON et al. proposed MonoSLAM, the first real-time monocular visual SLAM system, which determines camera poses through feature point extraction and matching, using EKF for state and map updates [2]. In 2020, LI et al. introduced DXSLAM, integrating CNN feature extraction into the SLAM framework. This method employs HF-Net for keypoint detection and global descriptors, proposes a global feature-based relocalization method, and achieves loop closure detection via HF-FBoW, demonstrating higher efficiency than traditional BoW [3]. TIWARI et al. developed pRGBD-SLAM, a narrow-to-wide baseline joint framework that combines monocular SLAM with CNN for depth prediction. By leveraging predicted depth to execute pseudo-RGBD SLAM and optimizing the depth network through wide baseline loss, it improves both pose and 3D structure [4], as illustrated in Figure 2.

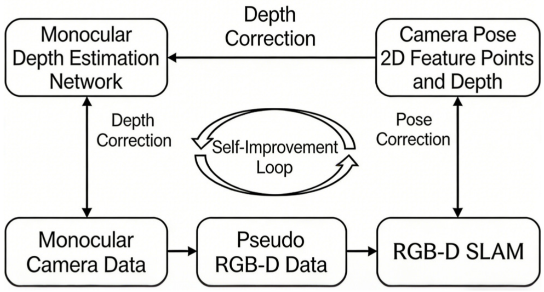


Figure 2. Work process of pRGBD-SLAM

3. PATH PLANNING AND NAVIGATION CONTROL STRATEGY

After completing environmental perception and mapping, the mobile robot's primary task is to autonomously navigate from the starting point to the processing or inspection station. To achieve efficient macro-path searching and real-time obstacle avoidance in micro-movements, the system employs a rigorous hierarchical planning architecture:

3.1. Global Path Planning (Based on A* Algorithm)

The system utilizes high-precision LiDAR-based grid maps and the A* algorithm to calculate the cost and heuristic values of each grid, thereby identifying the theoretically optimal path. This layer primarily plans the macro route from the starting point to the target point, ensuring both the shortest distance and safety. As shown in Figure 3.

3.2. Local Path Planning (Based on Dynamic Window Algorithm DWA)

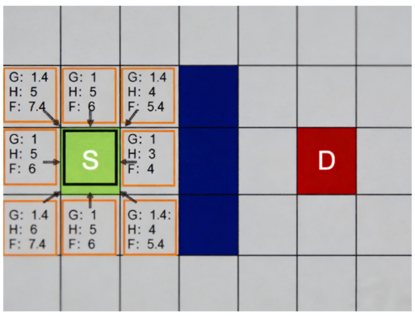


Figure 3

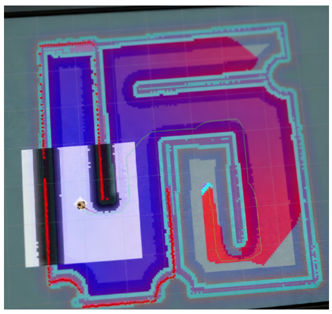


Figure 4

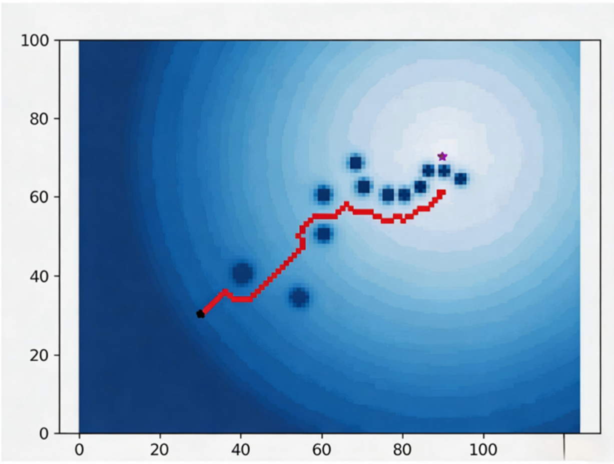
Figure 3. A* Schematic diagram of the algorithm's global path planning

Figure 4. Flowchart of DWA's local path planning

To address temporary obstacles in the workshop (e.g., moving forklifts), the system leverages ultrasonic sensors 'proximity detection data and applies the dynamic window method to recalibrate speed commands within milliseconds. By defining an acceleration range (dynamic window) for the robot's current speed, the algorithm evaluates trajectory safety and target alignment under each speed command set. It generates real-time motion commands based on velocity magnitude, enabling dynamic obstacle avoidance as shown in Figure 5.

3.3. Obstacle Avoidance Algorithms (Artificial Potential Field APF and Vector Field Histogram VFH)

To prevent A* path failure due to sudden obstacles, the system incorporates long-range repulsion from artificial potential field and real-time obstacle density statistics from vector field histograms. By adjusting the weights of these two components, when the global path fails, the system rapidly switches to emergency mode. It uses repulsion to push the robot away from obstacles and leverages density statistics to quickly identify safe movement directions, thereby restoring motion swiftly. As shown in Figures 5 and 6.



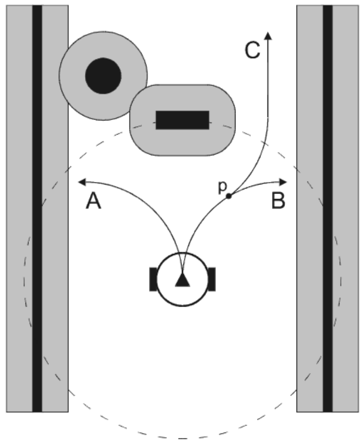


Figure 5 Figure 6

Figure 5. Schematic diagram of APF obstacle avoidance;

Figure 6. Schematic diagram of VFH obstacle avoidance

4. CONCLUSION

This paper provides a systematic review of the application status of multi-sensor fusion SLAM technology in mobile robot systems for machining inspection. In summary, multi-sensor fusion has become an inevitable choice for enhancing mobile robots' perception capabilities in complex industrial environments through complementary advantages. The phased and hierarchical technical approach, exemplified by "LIDAR for coarse positioning and obstacle avoidance, while vision and IMU achieve fine positioning and pose tracking," has proven effective in practice. Meanwhile, the ROS-based collaborative control strategy combining "global planning (A*) + local re-planning (DWA) + real-time obstacle avoidance" offers a reliable solution for safe navigation in dynamic environments. Looking ahead, research in this field will exhibit the following trends:

(1) Semantic and Intelligent SLAM: Semantic SLAM will be a key focus. Robots will not only build geometric maps but also recognize and understand semantic objects in the environment (e.g., machine tools, doors, workbenches), enabling task-oriented navigation and interaction.

(2) Deep learning integration: By leveraging deep learning networks for feature extraction, dynamic object segmentation, and even end-to-end pose estimation, the system's understanding and generalization capabilities in abnormal scenarios will be significantly enhanced.

(3) Edge Computing and Lightweight Deployment: With the advancement of dedicated AI chips and edge computing devices, researchers are developing more lightweight and efficient fusion

models and algorithms to enable real-time deployment of high-performance SLAM systems on mobile robot platforms.

(4) Standardized and systematic evaluation: Promote the establishment of standardized testing scenarios and performance evaluation systems for industrial applications, facilitating technological maturity and industrial adoption.

The advancement of mobile machining inspection robots is propelling intelligent manufacturing toward greater flexibility and autonomy. Continuously overcoming key technical challenges in multi-sensor fusion SLAM is crucial for unlocking the full potential of robots and establishing truly intelligent factories.

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