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MULTI SENSOR FUSION FOR MOBILE ROBOT PERCEPTION

BIN ZHANG

Belarusian State University of Informatics and Radioelectronics, Republic of Belarus

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Abstract. This paper proposes a multi-sensor fusion system using Light Detection and Ranging (LiDAR), Inertial Measurement Unit (IMU), RGB-Depth (Red Green Blue-Depth) camera, and ultrasonic sensors to overcome single-line LiDAR limitations in robot navigation. By integrating a tightly-coupled LiDAR-IMU odometry and vision-based 3D mapping, the design significantly improves positioning accuracy and obstacle awareness. The distributed architecture ensures robust performance for autonomous mobile platforms.

Keywords: 2D LiDAR, IMU, RGB-D Camera, ROS2, SLAM, Obstacle Avoidance.

Introduction

With the rapid development of artificial intelligence and sensor technologies, mobile robots have gradually expanded from industrial automation to daily life scenarios such as healthcare, logistics, and domestic service [1]. Whether it is automated guided vehicles in factories, delivery robots in hotels, or vacuum cleaning robots in home environments, all require the ability to operate safely and reliably in unknown or dynamic environments. LiDAR, regarded as the eyes of mobile robots, has become a core sensor for autonomous navigation due to its high ranging accuracy and fast response speed [2]. Within the ecosystem of the open-source robot operating system Robot Operating System 2 (ROS2) [3], the development of low-cost mobile robot platforms has become a current research hotspot.

Single-line LiDAR, with its advantages of high measurement accuracy, good real-time performance, and controllable cost, has become one of the core sensors in mobile robot perception. However, when the system relies solely on a single LiDAR sensor to simultaneously undertake both obstacle avoidance and environmental mapping tasks, it faces several unavoidable theoretical limitations and engineering challenges. Firstly, in terms of perception dimensionality, single-line LiDAR can only obtain two-dimensional planar information and cannot perceive obstacle height, leading to the risk of missed detection of low-height or suspended objects. Additionally, the near-field blind zone limits the response space for close-range collision avoidance. Secondly, at the level of localization and mapping, pure LiDAR odometry lacks the motion priors provided by wheel encoders or IMU, making it prone to pose mutation due to scan matching failure during rapid rotation or movement. Furthermore, single-line LiDAR has perception blind zones for special materials such as glass and mirrors, struggles to distinguish between static obstacles and moving objects in dynamic environments, and the entire perception system suffers from the vulnerability of a single point of failure.

To validate the aforementioned limitations, this study proposes a mobile robot platform featuring a distributed control system with cooperative upper and lower computers (see Figure 1). In terms of system architecture, the upper computer utilizes a Raspberry Pi 4B running the Ubuntu operating system and the ROS2 Humble framework, primarily responsible for LiDAR data acquisition, obstacle avoidance algorithm computation, and visualization of point cloud data. The lower computer employs an Arduino Uno, communicating with the upper computer via Universal Serial Bus（USB） serial port, receiving speed control commands, performing inverse kinematics calculations for the Mecanum wheels, and ultimately controlling four Direct Current (DC) motors through an L293D motor driver module. This division of labor between the upper and lower computers ensures both the operational efficiency of complex algorithms and the real-time performance of low-level control, providing a reliable hardware foundation for subsequent obstacle avoidance and mapping experiments. It decouples complex algorithm processing from real-time low-level control, fully leveraging the performance advantages of different processors.

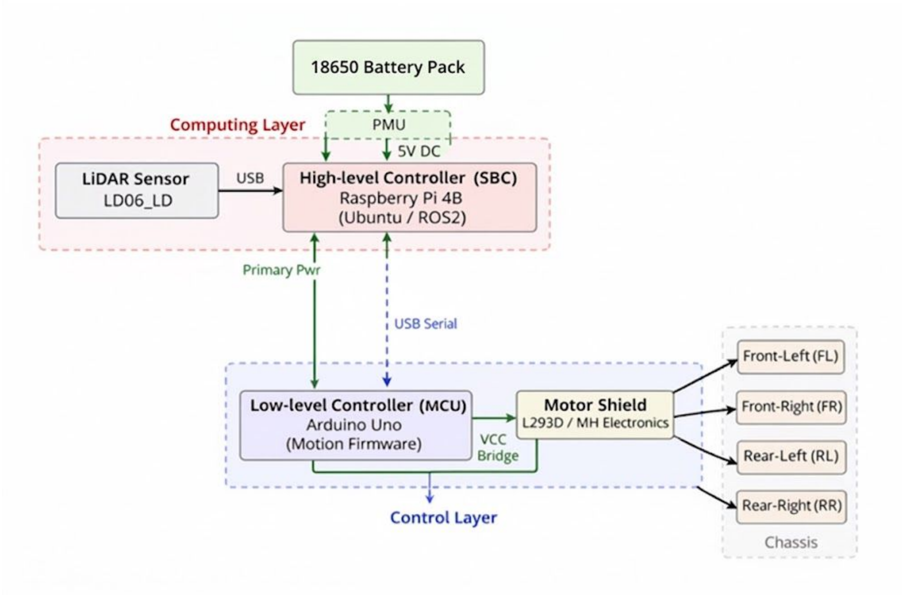

Figure 1. System hardware architecture diagram

In preliminary Simultaneous Localization and Mapping (SLAM) mapping and obstacle avoidance experiments, the three theoretical issues mentioned above were fully validated in the real system. The experimental phenomena are specifically manifested in the following three aspects:

First, Mapping Drift Caused by Motion Estimation Degradation. Due to the system not being equipped with an IMU or high-precision wheel encoders, the pure LiDAR odometry exhibited significant mapping drift during rapid rotation and movement, specifically manifested as point cloud ghosting and pose offset (see Figure 2). Furthermore, the single LiDAR sensor has an inherent defect during the mapping process: when dynamic objects appear in the environment, the system cannot distinguish them from static obstacles, leading to anomalies or even crashes in the mapping results.

Second, Obstacle Missed Detection Caused by Spatial Perception Limitations. The LD06 2D LiDAR is mounted on the robot's roof (approximately 10 cm above the ground) and can only acquire two-dimensional scan data within the horizontal plane, resulting in significantly insufficient three-dimensional spatial perception capability. Although the radar demonstrates good obstacle avoidance response to suddenly appearing obstacles within the horizontal plane, when the obstacle height is below the LiDAR scan plane, the system fails to detect it entirely, leading to direct collisions.

Third, Lack of Environmental Adaptability and System Robustness. When the robot approaches glass windows or mirrored furniture, severe missing occurs in the LiDAR point cloud over large reflective surfaces, causing local localization loss. Moreover, the system relies entirely on LiDAR as the sole perception source. When the sensor experiences temporary disconnection due to loose interfaces or other reasons, the robot immediately falls into a "perception failure" state, unable to continue mapping or perform obstacle avoidance tasks.

Addressing the three problems above, this paper proposes corresponding solutions, which will be elaborated in subsequent sections: First, to address spatial perception limitations, an RGB-D camera will be introduced to obtain obstacle height information, compensating for the perception blind zones outside the LiDAR plane. Second, to tackle motion estimation degradation, an IMU will be fused with LiDAR to construct a tightly-coupled odometry, suppressing pose drift during rapid motion and on rough terrain. Finally, to improve environmental adaptability and system robustness, fault detection and degraded operation mechanisms will be added to the obstacle avoidance strategy, along with discussions on handling dynamic objects.

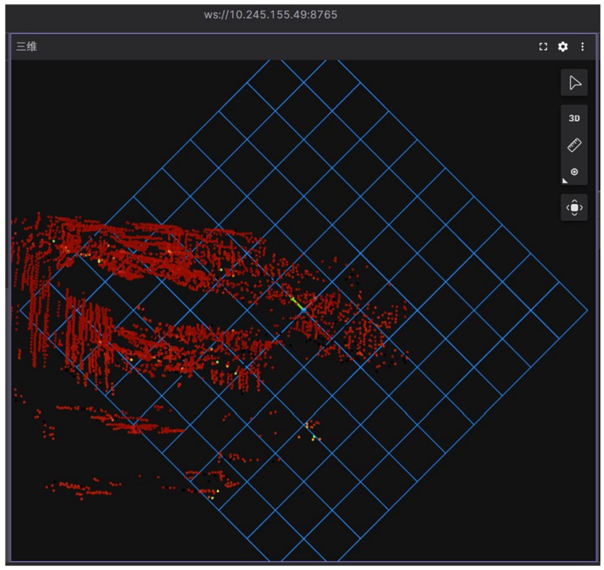

Figure 2. Mapping drift

Suppression of Motion Estimation Degradation: Design of LiDAR-IMU Fusion Odometry

Addressing the pose drift problem of pure LiDAR odometry during rapid rotation, in feature-sparse environments, and on rough terrain identified in the experiments, this paper proposes integrating an IMU with LiDAR based on the structure shown in Figure 1 to construct a tightly-coupled LiDAR-IMU odometry. An MPU6050 six-axis IMU is selected, with an output frequency of 200 Hz. Time alignment with the LiDAR is achieved using ROS2's joint time synchronization mechanism. The fusion algorithm adopts a tightly-coupled framework based on an Error State Kalman Filter [4]: IMU data provides high-frequency state propagation for pose prediction between two LiDAR scans; upon arrival of a new LiDAR scan, feature points are extracted and scan-matched against the local map to obtain observation residuals; the filter update corrects the accumulated IMU error and estimates IMU biases online. In feature-sparse environments, the system adaptively increases the weight of the IMU prediction to avoid pose mutation caused by scan matching failure [4]. To address changes in vehicle pitch angle on rough terrain, the attitude angles estimated by the IMU are fed back to the LiDAR point cloud preprocessing module. The raw point cloud is rotationally corrected before scan matching, effectively suppressing mapping distortion caused by vehicle tilt. This fusion odometry provides a stable pose estimation foundation for the entire system, supporting the subsequent implementation of mapping and obstacle avoidance functions.

Enhancement of System Robustness: 3D Environmental Perception Based on an RGB-D Camera

Building upon the stable pose estimation provided by the LiDAR-IMU fusion odometry, this paper introduces a RGB camera as the primary mapping sensor to address the vertical perception blind zone problem of single-line LiDAR. The LD06 LiDAR can only acquire two-dimensional horizontal information, failing to detect low-height or suspended obstacles and unable to identify obstacle categories. Therefore, the system defaults to using the RGB camera as the core mapping sensor, running an Oriented Fast and Rotated Brief SLAM2 (ORB-SLAM2) [5] visual-inertial tightly-coupled SLAM system. In environments with good lighting and rich texture, it constructs a 3D point cloud map containing obstacle height information and, combined with lightweight object detection algorithms, identifies obstacle types that LiDAR cannot perceive.

Ensuring seamless connect of maps constructed by the two different sensors, the system does not support simultaneous operation of LiDAR and the RGB camera. Consequently, a manual switching mode is adopted in practical deployment: By default, the RGB camera is responsible for mapping and object recognition. When the robot enters scenes with insufficient lighting, texture scarcity, or excessive dynamic objects, leading to a decline in visual SLAM tracking quality, the user can manually shut down ORB-SLAM2 via upper computer commands and switch to LiDAR SLAM mode. In this mode, the system relies on the LiDAR-IMU fusion odometry to maintain mapping and localization stability. The pose information provided by this odometry is used to align the coordinate systems of the maps, ensuring seamless connection of maps.

Regarding obstacle avoidance functionality, regardless of which sensor is currently used for mapping, the LiDAR always remains active as the primary obstacle avoidance sensor. Leveraging its high ranging accuracy and fast response speed, LiDAR ensures real-time obstacle avoidance performance for the robot in most scenarios. Simultaneously, the position information of low-height and suspended obstacles identified by the RGB camera during mapping is synchronized to the obstacle avoidance module. When the robot approaches these areas, the system triggers supplementary obstacle avoidance responses, forming a dual mechanism with LiDAR as the primary and the RGB camera as the secondary sensor. This design prioritizes the RGB camera for mapping, fully utilizing its advantages in 3D perception and object recognition, while relying on LiDAR for real-time obstacle avoidance, achieving a balance between perception completeness and operational safety under limited computational resources.

Enhancement of System Robustness: Near-Field Obstacle Avoidance and Fault Tolerance Using Ultrasonic Sensors

At the obstacle avoidance functional level, LiDAR, due to its high ranging accuracy and fast response speed, is always activated as the primary obstacle avoidance sensor. It is responsible for real-time detection of and response to obstacles within the horizontal plane, ensuring operational safety in most scenarios. However, 2D LiDAR has inherent limitations: its scanning plane is fixed, rendering it completely ineffective against transparent or reflective materials like glass and mirrors, and it possesses a near-field blind zone. Mounted approximately 10 cm above the ground on the robot's top, areas above and below its scanning plane, particularly low-height obstacles and uneven pavement, are entirely outside its detection range.

To compensate for these defects, this section introduces an RGB camera and ultrasonic sensors as supplementary obstacle avoidance methods. In its default mapping mode, the RGB camera continuously identifies low-height obstacles, suspended obstacles, and uneven pavement (ground height changes) using visual SLAM and object detection algorithms, recording the location information of these hazardous areas in the map. When the robot subsequently approaches these pre-identified areas, the obstacle avoidance module proactively triggers detour or deceleration responses. However, the RGB camera may fail under conditions of insufficient lighting, texture scarcity, or excessive dynamic objects, rendering it unable to identify newly appearing obstacles in real-time.

Two to three HC-SR04 ultrasonic sensors are installed on the front of the robot chassis to provide gapless scanning of the area directly in front of the robot, focusing on detecting low-height obstacles below the LiDAR's scanning plane. Ultrasonic sensors are insensitive to transparent and reflective materials, effectively detecting obstacles like glass and mirrors that LiDAR struggles with. In the obstacle avoidance logic, LiDAR always holds the first priority, responsible for real-time detection of the vast majority of obstacles, with its safety threshold set at 30 cm. The ultrasonic sensors act as a second line of defense, configured with a more conservative safety threshold of 15 cm. When LiDAR fails to trigger avoidance due to special materials, blind zones, or height limitations, and an ultrasonic sensor detects an obstacle within 15 cm, the system immediately executes deceleration and backward turning to re-plan the path. The RGB camera handles the predictive avoidance of pre-identified dangerous areas, complementing the real-time detection capability of the ultrasonic sensors: the camera addresses the avoidance of known hazardous areas, while the ultrasonic sensors handle real-time detection of sudden transparent obstacles and low-height obstructions.

Conclusion

This chapter addresses the inherent limitations of single-line LiDAR by introducing an IMU, an RGB camera, and ultrasonic sensors, thereby constructing a multi-sensor fusion perception and localization system. The LiDAR-IMU fusion odometry mitigates pose drift, providing a stable pose foundation for the system. The RGB camera serves as the default mapping sensor, building 3D point cloud maps via ORB-SLAM2 to solve the vertical perception blind zone problem. The ultrasonic sensors act as supplementary obstacle avoidance tools, filling gaps related to transparent materials and the near-field blind zone. The three sensors have distinct roles, collectively enhancing the system's perceptual completeness and operational safety.

Due to the performance limitations of the hardware platform, this study has the following shortcomings: The computational load on the Raspberry Pi is high, potentially leading to lag during prolonged operation; limited battery life restricts the ability to support large-scale mapping tasks; cumulative drift remains unavoidable during long-duration mapping; the system lacks the ability to detect uneven pavement (ground height changes) in dark environments where the RGB-D camera fails; and the effectiveness and reliability of the fault-tolerant degraded mode require further experimental validation. Given the constraints of the aforementioned hardware platform and sensory capabilities, the experiments in this research phase will primarily be conducted in structured indoor environments, including home settings, laboratories, and corridors, to validate the basic functionality and cooperative mechanisms of the multi-sensor fusion framework. Adaptability testing in outdoor environments and complex unstructured scenarios is planned as future research direction.

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