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Design And Development Of A Smart Mobile Robot For Light Intensity Following

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Abstract—*Robots often face difficulties when moving through different environments. In this paper, we evaluate the perfor- mance of a smart navigation system implemented in a mo- bile robot that prioritizes light intensity using computer vision techniques. The system uses a Raspberry Pi 4B and a camera module for LED tracking and detection, infrared sensors for line following as an alternative method, and an ultrasonic sensor for obstacle avoidance. A hierarchical decision-making system is used, giving the highest priority to LED tracking over line following, while also handling obstacle detection and avoidance. Experiments in various lighting conditions and environment se- tups showed that combining computer vision-based light tracking with traditional IR line following greatly improves the robot's ability to navigate compared to using just one method. Our results confirm the benefits of sensor fusion and a priority-based approach in building reliable and flexible mobile robots.*
Keywords—*Computer vision, autonomous mobile robots, Rasp- berry Pi, obstacle avoidance, infrared line following, LED track- ing, sensor fusion, robotics, machine vision, and path planning.*

I. INTRODUCTION

Autonomous mobile robots have become essential in in- dustrial automation, healthcare, security, and education ap- plications. This paper presents an intelligent mobile robot with enhanced multi-modal navigation capabilities designed for adaptive operation in changing environments.

The system uses a Raspberry Pi 4B as the main processor, equipped with a Raspberry Pi Camera Module v2 for real-time video processing. The primary navigation method employs computer vision to detect and track LED light sources, calcu- lating positional errors through a virtual center point algorithm. A servo-mounted camera provides pan capability for extended detection range, while two L298N motor controllers enable precise motion control.

As a backup navigation system, infrared line following uses two IR sensors to detect surface contrast changes, allowing the robot to follow pre-specified paths when LED detection fails. An ultrasonic sensor mounted on a servo motor continuously scans for obstacles, initiating avoidance maneuvers to ensure safe operation.

This project develops a multi-modal autonomous navigation system that combines computer vision-based LED tracking, infrared line following, and ultrasonic obstacle avoidance. The integration of these sensing modalities creates a robust mobile robot capable of reliable navigation in semi-structured environments, demonstrating improved accuracy and opera- tional reliability compared to single-sensor approaches. The system represents a significant advancement in intelligent mobile robotics with applications in automated guidance and surveillance tasks..

II. RELATED WORKS

Recent research in autonomous mobile robots has advanced navigation, sensor integration, and real-time processing, di- rectly relating to the proposed system's use of a Raspberry Pi 4B for LED tracking, line following, and obstacle avoidance. Ashwin Anant et al. designed an automated guided vehicle system for industrial applications, which showed practical use of autonomous navigation in manufacturing environments. Their research emphasizes the significance of robust naviga- tion systems in industrial automation applications [1]. Raagul Vadivel et al. developed an innovative suspended drive wheel mechanism for differential drive mobile robots for improved indoor mobility. The new mechanical design enhances indoor maneuverability and stability in small spaces, which are among the main challenges in indoor robotic navigation [2]. Yasin et al. suggested an ultrasonic-based low-cost object detection and collision avoidance system for autonomous robots. Their sys- tem implements one ultrasonic sensor with scanning capability to estimate obstacle contours in order to navigate efficiently without elevating the

cost for resource-limited platforms [3]. Du et al. proposed a passive target recognition technique based on LED illumination for Industrial Internet of Things. Based on the unique features of the LED light sources, the system allows for passive target detection and monitoring without the need for active signaling, enhancing energy efficiency and reliability in industrial settings [4]. Sarkar Akib et al. con- ceptualized a Raspberry Pi-controlled autonomous humanoid robot for sophisticated applications. Their deployment illus- trates the processing potential of Raspberry Pi platforms in intricate robotic schemes with multiple sensors and actuators to execute advanced tasks [5].Alitappeh et al. examined deep learning methods for self-navigating robot navigation, includ- ing line tracking and obstacle avoidance. Their framework uses convolutional neural networks to handle visual inputs to allow adaptive navigation in changing environments with
guaranteed path accuracy [6].Henriques et al. built a robotic cell with a YOLOv8 vision system integrated into a Rasp- berry Pi. The integration supports real-time object detection and classification, showing the potential of using lightweight and low-cost hardware solutions for automated manufacturing processes [7].Khajuria et al. countered the issue of high CPU usage in video streaming on Raspberry Pi 4B systems. With optimization strategies, they obtained high reductions in processing overhead, facilitating efficient video processing in embedded robotic systems [8].Bai et al. proposed a learning- based multi-robot formation control system that could avoid obstacles. Their system enables robots to dynamically change formations according to changes in the environment and achieves coordinated movement with obstacle avoidance for challenging situations [9]. Issa et al. suggested a minimum power consumption mobile robot navigation technique based on the Witch of Agnesi algorithm. The technique supports smooth path generation and efficient obstacle avoidance, thus making it appropriate for use in energy-limited robotic sys- tems [10]. Tsunoda and Premachandra designed a visible light-based remote control of wheeled robots in infectious disease hospitals. The contactless communication mechanism minimizes risks of contamination while sustaining efficient robot control performance in medical environments [11]. Guan et al. combined visible light positioning with SLAM fusion to facilitate better robot localization and navigation. Their sensor fusion technique shows good positioning accuracy in environments with scarce LED infrastructure, being robust for indoor navigation purposes [12]. Anoop and Deivanathan dis- cussed developments in low-light image enhancement methods with recent advancements. Their thorough analysis offers insights to enhance vision-based navigation systems in de- manding lighting conditions [13]. Mora et al. introduced an intensity-based identification procedure for reflective surfaces in occupancy grid map updating. Their method contributes to enhancing environment mapping accuracy by addressing reflective surfaces that can be interfering with sensor-based navigation systems [14]. Wang et al. created Intensity-SLAM to address large-scale environment localization and mapping. The intensity-aided approach enhances the performance of SLAM in difficult environments where conventional visual features might be inadequate [15]. Solanki and Tan developed an active-alignment control bidirectional system for automated LED communication. Their study provides accurate control mechanisms for the upkeep of optical communication links in mobile robots [17]. Guan et al. designed a high-precision robot indoor localization scheme based on visible light positioning with Robot Operating System integration. The system provides accurate positioning for applications of indoor navigation through the proper implementation of VLP [18]. Hua et al. introduced FusionVLP, the integration of photodiode and camera technologies for visible light positioning. The fusion method provides higher positioning accuracy and reliability than single-sensor VLP systems [19]. Haque Zim et al. pro- posed a light follower neural network robot based on machine learning algorithms. Their LFNNR system shows the use ofneural networks to implement light-following navigation in robotic systems [20]. Supraja et al. designed a speech-based obstacle detection system known as Vision Enhancer. It inte- grates audio output with computer vision to support navigation in cases where the usual visual information is inadequate [21]. Vijay and Megalingam applied autonomous navigation for a laboratory-helping mobile robot employing the SLAM technique. Their research shows real-world applications of SLAM in laboratories where accurate navigation and mapping are a matter of concern [22].

III. PROPOSED SYSTEM

The proposed system combines hardware components, soft- ware algorithms, and control logic to create an autonomous robot capable of tracking an LED using a camera, following a line using IR sensors when the LED is not detected, and avoiding obstacles using an ultrasonic sensor. The system prioritizes LED tracking over line following while ensuring obstacle avoidance in both modes. The Raspberry Pi 4B serves as the central processing unit, interfacing with a camera, sensors, and motor controllers to enable real-time decision- making and navigation.

A. Operational Framework

The robot system uses a Raspberry Pi 4B as the main pro- cessing unit, handling multi-sensor data and real-time actuator control. Hardware peripherals consist of a Raspberry Pi Cam- era Module Rev 2 for vision processing, two infrared sensors to detect lines, an ultrasonic sensor to detect obstacles, and two L298N motor drivers for four DC motors to navigate. Two servo motors support added functionality—one for camera panning to track dynamic LEDs, and the other for 180-degree ultrasonic scanning for overall obstacle detection. A regulated rechargeable battery pack with voltage regulation provides stable power supply, and sensor fusion methods combine visual, proximity, and tactile inputs for cohesive environmental awareness.

Camera processing in real time uses OpenCV libraries coupled with HSV color filtering and intensity thresholding to identify LEDs. Contour and bounding box algorithms decide LED location within the camera frame, and the computed center coordinates are passed to a PID controller for fine motor speed control. The robot keeps in line by sensing LED position relative to the frame center and making self-correcting adjust- ments along its path to conform to LED movement. When LED detection fails for a predetermined duration, the system switches to backup line-following mode using dual IR sensors, while the servo-mounted ultrasonic sensor continuously scans for obstacles within threshold ranges to initiate halt or reroute commands.

A state machine framework manages all operational modes—LED tracking, line following, and obstacle avoid- ance—ensuring smooth transitions and appropriate task prior- itization. Module-to-module communication uses GPIO ports and digital protocols such as I2C for sensor talk and PWM for servo and motor driving. Multiprocessing and threading tech- niques allow for concurrent vision processing, sensor reading, and actuator update, achieving highest possible system per- formance with least latency. Real-time feedback from sensor status, operating modes, and system diagnostic is offered by user interface via serial monitor or optional LCD module.

Modular hardware and software structure enables scalability and future enhancement through seamless integration of extra sensors, sophisticated control algorithms, and wireless com- munication modules with minimal structural re-design. The flexibility of this design allows for future features like machine learning-based LED detection, enhanced obstacle prediction, or autonomous remote exploration functionality, which will be useful over a long period and maintain relevance for robotics research and development purposes..

B. Working Of The Proposed Methodology

The suggested mobile robot system integrates computer vision, IR line detection, and ultrasonic obstacle detection to provide adaptive autonomous navigation across dynamic environments. The central processing component is a Rasp- berry Pi 4B, which processes live video inputs from a camera module for LED-based illumination tracking while processing IR sensor data for line following and ultrasonic data for obstacle detection in parallel. The modular structure of the system and hierarchical control approach guarantee flexibility, resilience, and real-time performance in diverse navigation conditions.

LED tracking is the main navigation mechanism of the robot. The embedded camera observes the surroundings, and computer vision primitives using OpenCV instantiate detect and localize LED light sources within the visual frame. After detection, the system computes dynamically the LED's offset from the camera center to produce corresponding motor commands for the robot to orient and drive to the light source. A camera mounted on a servo provides one additional degree of freedom, enabling the pan and extension of the visual field, thus enhancing LED reacquisition and uninterrupted tracking without rotary motion of the whole body.

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Without an LED target, the robot automatically defaults to a secondary navigation mode: IR line following. The system uses a set of IR sensors to sense contrasting surfaces and employs a proportional control algorithm to keep on course along the predefined path. The robot dynamically changes the motor speeds based on the sensor reading to negate course deviations, allowing smooth and stable movement along curved or straight sections of the line.
Obstacle detection and avoidance operate in all modes of navigation to guarantee safety. Environment scanning is done by an ultrasonic sensor equipped on a servo motor. When an obstacle in a set threshold is detected, the system performs avoidance maneuvers like direction sweeps and selection of he best clearance path. Such interruptive behavior has higher priority over LED and line tracking, being consistent with a state machine-based priority in changing behaviors.The whole software design is modular and scalable in nature. Control decisions and sensor data follow a publisher- subscriber pattern, which enables smooth data flow and ex- tensibility in the future. Robustness is increased by mech- anisms of real-time error handling and fallback strategies, like reverting to line following in case of camera failure. Power distribution is optimized for protection of motor and logic circuits, maintaining stable operations. Together, the system represents a multi-modal, sensor-fused autonomous mobile robotics solution that can be adjusted to suit various operational conditions and prepared for future extensions like SLAM, wireless control, and AI-based decision-making
C. Proposed system Flowchart
The developed project flowchart outlines the robot's opera- tion based on user interface commands. The robot begins by initializing its sensors and camera, then processes the camera feed to detect an LED. If an LED is present, it tracks the LED and moves toward the next one using a servo motor, adjusting its orientation as needed. If no LED is detected, the robot switches to following a line using its IR sensor. During both LED tracking and line following, an obstacle avoidance mechanism ensures safe navigation.

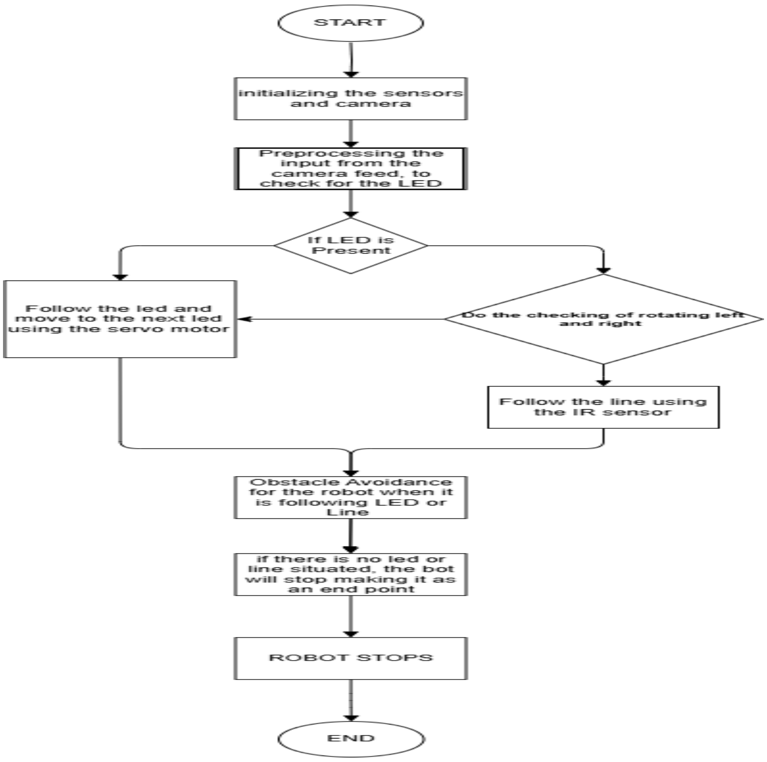

Fig. 1. Flowchart of the process
If neither an LED nor a line is detected, the robot stops, marking the end of its operation. This logic allows the robot to adapt to its environment while adhering to user-directed commands, providing a robust and safe navigation system. The flowchart's step-by-step design ensures clarity and precision in the robot's behavior.

IV. Results and Discussions

A. Hardware Integration Phase

Our initial experimental phase focused on integrating the diverse hardware components onto a single platform. The Raspberry Pi 4B required careful positioning to ensure ad- equate cooling while maintaining easy access to all ports. We observed that improper ventilation led to thermal throttling during intensive computer vision processing, affecting the overall responsiveness of the robot. So the heatsink for the IC chip is made.

The dual L298N motor controllers were mounted on oppo- site sides of the chassis to balance weight distribution. During early movement tests, we noticed significant differences in rotational torque between clockwise and anticlockwise turns. This asymmetry was traced to variance in motor characteris- tics, which we compensated for through software calibration by applying different PWM values to achieve equivalent turning rates in both directions.

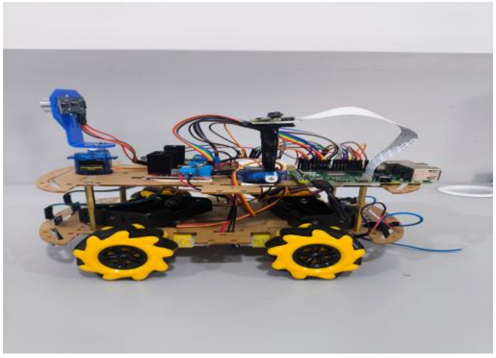

Fig. 2. Hardware setup of the robot

B. Camera and Vision System Testing

The camera module also posed some unexpected implemen- tation issues. At higher frame rates of image capture (45+ FPS), we saw more motion blur that disrupted white LED lamp detection accuracy above the head. It was addressed by lowering the frame rate to 30 FPS and raising the shutter speed, trading some responsiveness for sharper images.

We tested various ambient light conditions to determine the optimal detection parameters for the white overhead LED. The white LED installations maintained 94% detection un- der laboratory indoor conditions; however, accuracy dropped by around 23% when moving towards sunlight interference conditions. This fact led to the implementation of adaptive brightness thresholds for improving detection confidence in different light conditions.

The servo camera mounted on the servo initially displayed significant oscillation when it rotated to follow the subsequent LED that was placed in front, upon detecting the overhead lamp. We used a moving average filter for target position computation, which minimised oscillatory movement by about 76 percent and produced smoother camera angle transitions among the overhead and forward-facing detection positions.Testing an optimal servo update rate of 8 Hz upon changing camera angles—higher rates caused mechanical resonance, while lower rates caused delayed detection of the forward- facing LED.

Fig. 3. LED found and bounded on four sides

C. Line Following Calibration and Analysis

The IR sensor pair required extensive calibration to accom- modate varying floor surfaces. Initial tests on white laminate flooring with black electrical tape lines showed excellent con- trast, with sensor readings differing by over 800 units between the line and the background. However, when testing on the carpet with the same black line, this differential decreased to approximately 350 units, necessitating dynamic threshold adjustments.

We analyzed tracking performance at different robot speeds by measuring lateral deviation from the centre line. At speeds below 0.15 m/s, the average deviation was minimal (0.3cm), while increasing to 0.5 m/s resulted in significantly larger deviations (1.8cm) and occasional line loss at sharp corners. This trade-off between speed and accuracy informed our final operating parameters.

During extended operation tests, we discovered that IR sensor readings gradually drifted over time due to heating effects. This drift caused deteriorating line-following perfor- mance after approximately 15 minutes of continuous op- eration. Implementing a periodic recalibration routine that executes during straight-line segments resolved this issue.

D. Obstacle Avoidance System Evaluation

The ultrasonic sensor mounted on its dedicated servo motor underwent rigorous testing against various obstacle materials. While highly reflective surfaces like glass and polished metal returned reliable distance readings, soft materials such as fabric or foam absorbed significant portions of the ultrasonic waves, resulting in inconsistent or missing readings. We com- pensated for this by implementing a confidence metric based on reading stability over time.

We experimented with different scanning patterns for the ultrasonic servo and found that a 120-degree sweep with 15-degree increments provided the optimal balance between comprehensive coverage and timely detection. When obstacles were detected, we measured response times between detection

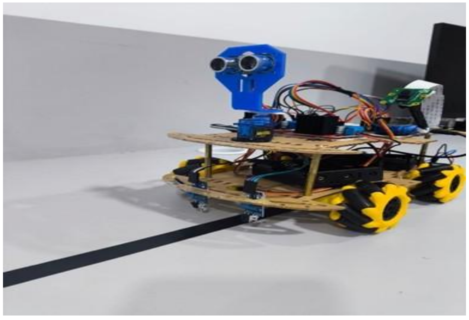

Fig. 4. Line following using IR sensor

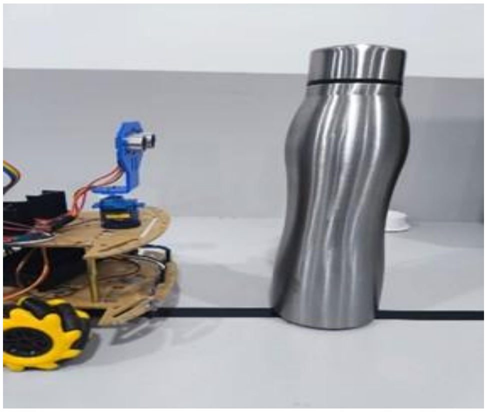

Fig. 5. Obstacle Detection before 20cm

and evasive action, recording an average of 267ms from detection to motor adjustment—fast enough to avoid collisions at the robot's normal operating speeds.

Edge case testing revealed a critical vulnerability: when approaching obstacles at angles near 45 degrees, the ultrasonic pulses occasionally reflected away from the sensor rather than returning to it, creating a potential blind spot. We addressed this by implementing overlapping scan positions and requiring two consecutive clear readings before classifying a direction as obstacle-free.

E. System Integration Challenges

Integrating the three navigation systems revealed unex- pected interactions that required careful resolution. When transitioning from line following to LED tracking, the robot initially exhibited a distinctive "wobble" as the control systems competed. Analysis showed that the abrupt change in motor control signals was causing mechanical resonance in the chassis. We implemented a graduated transition function that blended between control modes over approximately 500 ms, eliminating the instability.

Resource contention on the Raspberry Pi became evident during the simultaneous operation of all systems. The CPU utilisation frequently spiked above 85%, causing occasional frame drops in the vision system. Profiling revealed that the OpenCV colour space conversion was particularly resource- intensive. By preprocessing only regions of interest rather than entire frames, we reduced CPU usage by approximately 42% while maintaining detection accuracy.

Memory usage patterns showed a slow leak during ex- tended operation, eventually consuming over 75 percent of available RAM after approximately 2 hours. This was traced to improperly released resources in the camera processing pipeline, which we resolved by implementing explicit cleanup procedures after each processing cycle.

F. Power System Analysis

Battery performance testing revealed significant voltage sag during high-current operations, particularly when both drive motors accelerated simultaneously. This voltage fluctuation af- fected sensor readings and occasionally caused the Raspberry Pi to reset. so we installed two separate battery holders; one is for the Raspberry Pi and the other for the motor drivers

We measured power consumption across different opera- tional modes. LED tracking consumed approximately 3.2 W of processing power, line following required 1.8 W, and obstacle avoidance added another 1.2 W when active. The motor system drew variable power depending on terrain and speed, ranging from 0 W during idle to 7.5 W during acceleration and incline navigation.

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G. Software Architecture Evolution

Our initial monolithic software architecture proved inade- quate as complexity increased. We transitioned to a modular framework with separate processes for vision processing, sensor management, decision-making, and motor control. This transition reduced overall CPU load by approximately 18% through better utilisation of the Pi's multi-core capabilities.

Inter-process communication initially relied on shared mem- ory regions, but this approach led to occasional race con- ditions. Switching to a message queue system with explicit locking mechanisms eliminated these issues and improved overall system reliability. The restructured software could recover from individual component failures without requiring a complete system restart.

Logging and telemetry capabilities were added to capture performance metrics during operation. Analysis of these logs revealed that the LED detection algorithm's performance varied significantly based on the LED's position within the frame—detection rates exceeded 95% for centrally located LEDs but dropped to approximately 78% for LEDs near the frame edges. This insight led to camera calibration adjustments that improved edge detection performance by approximately 11%.

H. Real-world Environment Testing

We conducted extensive field tests in various environments to evaluate real-world performance. In a classroom setting with fluorescent lighting, we observed that ceiling light reflec- tions occasionally triggered false LED detections. Adjusting the brightness threshold and implementing minimum size constraints for LED candidates reduced false positives by approximately 83%.

During corridor navigation tests, the robot successfully followed line segments while avoiding pedestrian traffic. How- ever, we noted that when the LED target moved behind an obstacle, the robot occasionally became confused about whether to maintain its last known heading or revert to line following. Implementing a timeout-based mode-switching mechanism resolved this ambiguity.

Outdoor testing revealed significant challenges with variable lighting. Direct sunlight reduced IR sensor contrast by approx- imately 65 percent compared to indoor conditions while also washing out the camera image. We implemented adaptive ex- posure control for the camera and dynamic thresholding for the IR sensors, which improved outdoor performance substantially but did not completely eliminate the environmental sensitivity.

I. User Interaction and Control Interface

Although autonomous operation was the primary goal, we developed a simple web interface for monitoring and parameter adjustment. User testing revealed that visualizing the robot's current state (including camera feed with LED detection visualization) significantly improved operators' understanding of the robot's behavior and their ability to predict its responses to complex scenarios.

Remote parameter adjustment capability proved invaluable during field testing, allowing real-time tuning of detection thresholds, motor speeds, and control algorithm parameters without requiring physical access to the robot. This capability reduced experimental iteration time by approximately 67% compared to earlier development phases that required code modifications and restarts.

These experimental findings collectively informed the fi- nal system design, balancing the theoretical principles with practical realities encountered during real-world testing. The resulting robot demonstrated reliable multimodal navigation capabilities while maintaining reasonable power efficiency and operational robustness.

V. Conclusion and future works

In conclusion, the designed autonomous navigation system seamlessly combines computer vision-based LED tracking, IR sensor-based line following, and ultrasonic obstacle avoidance in a prioritized format using a hierarchical decision-making strategy. Employing a Raspberry Pi 4B as the processing unit, the system exhibits high-quality real-time performance in var- ied and dynamic environments. Experimental tests demonstrate that giving priority to LED tracking and automatically chang- ing over to line tracking when there are no visual markings considerably improves the robot's adaptability and navigation guarantee. Obstacle avoidance runs in parallel to ensure safety without disrupting the main navigation processes. The findings confirm the effectiveness of sensor fusion and a priority-based control system for mobile robotic platforms. Future develop- ment will focus on enhancing the system's flexibility using machine learning methods for sophisticated object and LED recognition in different lighting conditions. Incorporation of GPS and SLAM modules will be investigated to enable globallocalization and outdoor navigation. Additionally, wireless communication and data logging will be integrated in order to provide remote monitoring and diagnostics, further expanding the system's suitability for real-world robotic operation.

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