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A Color-Guided Autonomous Rover with Integrated Localization and Sensor-Fusion-Based Motion Control

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ABSTRACT

Accurate navigation in indoor industrial environments remains a major challenge, particularly in scenarios where Global Positioning System (GPS) signals are unavailable and physical factors such as wheel slippage and surface irregularities introduce motion errors. Conventional robotic systems often rely on open-loop control or basic proximity sensing, which lack feedback correction and result in cumulative positional drift over time. To overcome these limitations, this work presents a Color-Assisted Autonomous Rover (CAAR) designed for precise localization within a structured grid-based environment using a multi-sensor fusion approach. The system is built around an ESP32 Microcontroller Unit (MCU) and integrates a Micro-Electro-Mechanical Systems (MEMS)-based Inertial Measurement Unit (IMU) along with quadrature encoders to implement closed-loop Proportional-Integral-Derivative (PID) control, enabling continuous correction of motion errors during both linear and rotational movements. A dual Inter-Integrated Circuit (I2C) communication setup is employed to efficiently manage high-frequency motion data separately from lower-frequency sensor inputs, including data from a TCS34725 Red-Green-Blue (RGB) color sensor. The navigation framework converts Cartesian coordinate inputs into sequential movement commands, allowing the rover to systematically traverse predefined grid points. Upon reaching each location, the system performs color-based validation to confirm positional accuracy, providing an additional layer of environmental feedback. A WebSocket-based interface facilitates real-time communication, supporting both manual operation and autonomous navigation modes. Experimental results demonstrate a significant reduction in drift and improved consistency compared to traditional methods, making the system highly suitable for reliable indoor automation tasks.

Keywords: Indoor Navigation, Mobile Robotics, RGB Color Sensing, WebSocket Interface, Grid-Based Localization, Quadrature Encoders.

1. INTRODUCTION

The transformation of industrial operations in recent years has been largely driven by the principles of Industry 4.0 (I4.0), which emphasize the integration of intelligent machines, interconnected systems, and data-centric decision-making. In this evolving landscape, autonomous mobile robots have emerged as a key technology for streamlining internal logistics, material handling, and workflow automation within indoor environments such as smart factories, warehouses, and distribution centers. These environments are typically structured with predefined layouts to maximize efficiency, yet ensuring accurate and reliable navigation within them remains a technically demanding problem. Unlike outdoor systems, where the Global Positioning System (GPS) provides consistent localization, indoor environments block or distort such signals due to walls, metallic structures, and interference, making GPS-based navigation impractical. As a result, robots must rely on onboard sensing, motion estimation, and environmental referencing techniques to determine their position and movement.

In the early stages of indoor automation, navigation was achieved using Automated Guided Vehicles (AGVs), which followed fixed paths defined by physical infrastructure such as embedded wires,

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magnetic strips, or optical tracks. These systems were highly reliable and safe but lacked flexibility, as any change in route required physical modification of the environment. With advancements in robotics, Autonomous Mobile Robots (AMRs) were introduced, offering greater adaptability by using onboard sensors to navigate dynamically. Technologies such as Light Detection and Ranging (LiDAR), ultrasonic sensors, and wheel encoders allowed these robots to perceive their surroundings and estimate displacement through odometry. However, these methods introduced a major limitation known as dead reckoning drift, where small measurement errors in wheel rotation or motion accumulate over time, leading to significant deviations from the robot's actual position.

To address these limitations, the integration of Micro-Electro-Mechanical Systems (MEMS) sensors brought a major improvement in navigation accuracy. Devices such as Inertial Measurement Units (IMUs) provide continuous data on acceleration and angular velocity, enabling robots to estimate orientation and detect motion changes in real time. When combined with encoder data using sensor fusion techniques, these systems significantly reduce heading errors and improve positional estimation. Furthermore, the use of closed-loop control strategies, particularly Proportional-Integral-Derivative (PID) control, allows robots to continuously correct their motion based on feedback. This ensures stable trajectory tracking, compensates for mechanical variations between motors, and minimizes the effects of surface irregularities and slippage.

The demand for precise indoor navigation has increased significantly with the rapid growth of automation in logistics and manufacturing sectors. Modern warehouses and production facilities require robots to operate with high accuracy, consistency, and reliability to maintain efficiency. Despite technological progress, traditional open-loop motor systems still exhibit positional errors due to environmental factors, mechanical wear, and load variations, creating a gap between expected and actual performance. To overcome this challenge, contemporary robotic systems adopt hybrid navigation approaches that combine internal motion estimation with external validation methods. Techniques such as visual markers, color-based identification, or environmental landmarks are used to periodically verify and correct the robot's position, providing a form of ground truth reference.

This combination of sensor fusion, feedback control, and environmental validation enables robots to achieve significantly higher levels of accuracy and robustness compared to conventional methods. By continuously correcting errors and adapting to changing conditions, these systems can maintain reliable operation over long durations. As a result, modern indoor robotic platforms are capable of supporting complex, precision-driven tasks in industrial automation, including inventory management, automated transportation, and coordinated multi-robot operations, ultimately contributing to improved productivity, safety, and operational efficiency.

2. LITERATURE SURVEY

Doucet, et al. [1] presented a comprehensive theoretical and practical analysis of Sequential Monte Carlo methods, commonly known as particle filters, for addressing nonlinear and non-Gaussian state estimation problems in robotics. Their work explained how traditional estimation techniques often fail in complex environments where uncertainty is not normally distributed. They detailed the mathematical foundation of particle filters, including importance sampling, proposal distribution design, resampling strategies, and weight normalization. The study demonstrated how particle filters can approximate posterior probability distributions using a set of weighted samples, making them highly effective for localization tasks under uncertainty. Additionally, they discussed practical challenges such as particle degeneracy and sample impoverishment, proposing solutions like adaptive resampling and improved proposal functions to enhance performance in real-time applications. Alarifi, et al. [2] conducted an in-depth review of Ultra-Wideband indoor positioning systems, focusing on their signal characteristics, system architecture, and localization techniques. They explained how UWB technology uses extremely

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short-duration pulses to achieve high temporal resolution, enabling precise distance measurement through methods such as Time of Arrival and multilateration. Their study analyzed system performance in complex indoor environments affected by multipath propagation and non-line-of-sight conditions, demonstrating the robustness of UWB compared to conventional radio-frequency systems. However, they also highlighted key limitations, including high infrastructure costs, synchronization requirements between anchor nodes, calibration complexity, and increased power consumption, which restrict its widespread adoption in cost-sensitive robotic platforms. Grisetti, et al. [3] provided a detailed tutorial on graph-based Simultaneous Localization and Mapping (SLAM), presenting localization and mapping as a global optimization problem over a graph structure. Their work described how robot poses are represented as nodes, while edges encode spatial constraints derived from sensor measurements such as odometry and scan matching. They explained optimization techniques, including nonlinear least squares and sparse matrix methods, which enable efficient computation even in large-scale environments. A major contribution of their study was the emphasis on loop closure detection, which allows the system to identify previously visited locations and correct accumulated drift, thereby maintaining global consistency. They also discussed challenges related to computational efficiency, scalability, and real-time implementation in practical robotic systems.

Chen, et al. [4] surveyed the application of deep learning techniques in visual localization and mapping, providing a comprehensive comparison between traditional geometric approaches and modern data-driven methods. Their study highlighted how convolutional neural networks and learned feature descriptors improve robustness against variations in lighting, viewpoint, and environmental dynamics. They also explored end-to-end pose regression models that directly estimate camera position from raw image data, reducing reliance on handcrafted feature extraction. Furthermore, the authors examined hybrid systems that integrate deep learning with classical SLAM pipelines to enhance performance. Despite these advantages, they identified significant limitations such as the need for large labeled datasets, high computational and memory requirements, and challenges in deploying these models on embedded or real-time robotic platforms. Groves, et al. [5] presented an extensive study on integrated navigation systems that combine multiple sensing modalities, including GNSS, IMU, and additional sensors, through sensor fusion techniques. Their work explained various integration architectures, such as loosely coupled and tightly coupled systems, and analyzed how errors propagate across different sensors. They demonstrated that combining inertial measurements with external references significantly reduces drift and improves overall positioning accuracy, particularly in environments where GNSS signals are weak or unavailable. The study also discussed advanced filtering techniques and redundancy strategies that enhance system robustness, making it a foundational reference for multi-sensor navigation frameworks. Endres, et al. [6] evaluated RGB-D SLAM systems that integrate visual and depth sensing for indoor localization and mapping. Their work provided a detailed comparison of different SLAM implementations using depth cameras, analyzing performance in terms of accuracy, robustness, and computational efficiency. They explained how depth information resolves scale ambiguity present in monocular systems and improves feature matching reliability. Experimental results showed that combining color and depth data significantly enhances mapping precision and trajectory estimation. However, they also identified challenges such as sensor noise, sensitivity to reflective or transparent surfaces, limited sensing range, and increased computational requirements, which can affect real-time performance on embedded robotic platforms. Aggarwal, et al. [7] presented a detailed study on calibration and error modeling of Micro-Electro-Mechanical Systems inertial sensors, focusing on improving the accuracy of low-cost IMU units used in robotic applications. Their work identified major sources of error such as bias instability, scale factor variation, axis misalignment, and noise. They introduced systematic calibration procedures, including both static and dynamic testing methods, to

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estimate and compensate for these errors. Additionally, they developed stochastic models to characterize sensor noise and drift behavior over time. Their findings demonstrated that proper calibration significantly enhances measurement reliability and reduces long-term drift, making it essential for precise motion tracking and navigation systems.

Fuentes-Pacheco, et al. [8] conducted a comprehensive survey of visual SLAM techniques, classifying existing approaches into feature-based and direct methods. Their work analyzed key stages of visual SLAM, including feature detection, descriptor matching, motion estimation, and map representation. They compared different methods based on robustness, accuracy, and computational efficiency, particularly in real-time applications. The study also highlighted practical challenges such as sensitivity to illumination changes, scale ambiguity in monocular systems, and hardware limitations in embedded platforms. They concluded that while visual SLAM offers rich environmental perception, its performance is highly dependent on scene conditions and computational resources. Cadena, et al. [9] provided a broad and influential survey on the evolution of Simultaneous Localization and Mapping techniques, covering developments from early probabilistic methods such as Extended Kalman Filter-based SLAM to modern optimization-based approaches. Their work categorized SLAM systems based on representation and inference strategies, analyzing their advantages and limitations in terms of scalability, accuracy, and computational efficiency. They emphasized the importance of robustness in long-term autonomous operation and discussed emerging trends such as semantic SLAM, multi-sensor fusion, and lifelong mapping, where robots continuously update their environmental knowledge. Ahmed, et al. [10] presented a comprehensive overview of the evolution of Global Navigation Satellite System and Global Positioning System technologies, describing their historical development, system architecture, and applications. Their study highlighted how satellite-based positioning systems have improved global navigation accuracy and coverage over time. However, they also emphasized significant limitations in indoor environments, including signal attenuation caused by buildings, multipath interference, and reduced satellite visibility. These challenges make GNSS-based localization unreliable indoors, reinforcing the need for alternative approaches such as sensor fusion and vision-based systems. Dellaert, et al. [11] introduced a probabilistic framework for localization and mapping using factor graphs, representing robot states and environmental features as variables connected through measurement constraints. Their work explained how nonlinear optimization and smoothing techniques can be applied to estimate the most probable state of the system. They highlighted the advantages of factor graph methods in handling large-scale problems, enabling incremental updates, and efficiently managing loop closure constraints. The use of sparse matrix structures further improved computational efficiency, making this approach highly suitable for complex and scalable robotic applications. Al-Okby, et al. [12] reviewed Ultra-Wideband-based Real-Time Locating Systems for indoor positioning, focusing on system design, signal behavior, and localization algorithms. Their study explained how UWB technology achieves high positioning accuracy through precise time-based measurements such as Time Difference of Arrival. They evaluated system performance under challenging indoor conditions, including multipath interference and non-line-of-sight scenarios. Despite achieving centimeter-level accuracy, they identified limitations such as high deployment cost, infrastructure dependency on multiple anchor nodes, synchronization complexity, and increased power consumption, which restrict its applicability in low-cost and lightweight robotic systems.

3. PROPOSED SYSTEM

The system is developed as a comprehensive embedded control and autonomous navigation framework that integrates user interaction, sensing, decision-making, control algorithms, and actuation using the ESP32 microcontroller as the central processing unit as illustrated in Fig. 1. The architecture supports dual operational modes, namely grid-based autonomous navigation and manual control, both of which

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are accessed through HTML-based user interfaces hosted on an onboard web server running on specific ports for HTTP and WebSocket communication. User inputs such as directional commands, start/stop actions, and navigation triggers are transmitted via WebSocket, enabling low-latency, bidirectional communication between the interface and the controller. The navigation engine forms the core of the system, incorporating closed-loop PID control algorithms for both heading correction and distance regulation, where proportional, integral, and derivative components dynamically minimize errors in orientation and displacement.

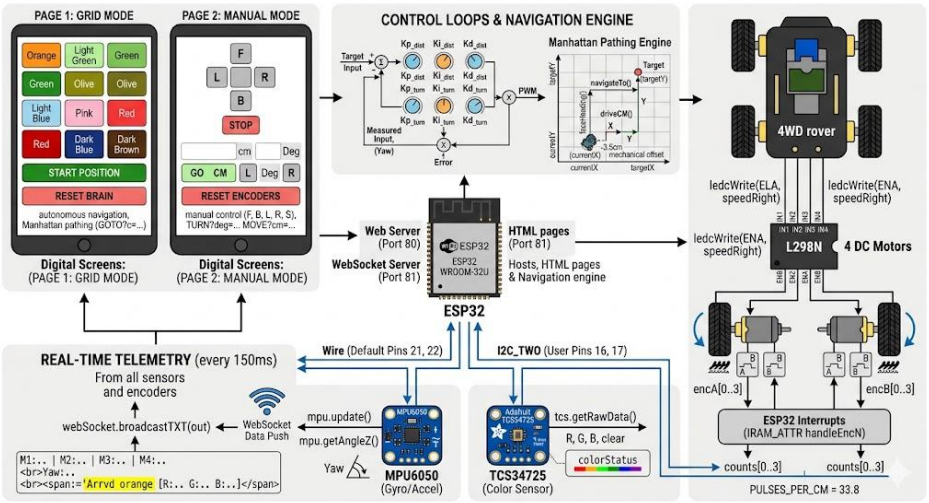


Fig. 1: Proposed system architecture.

The sensing subsystem integrates multiple hardware components including the MPU6050 IMU for real-time yaw and motion tracking, the TCS34725 color sensor for detecting grid-based color nodes used in path planning, and quadrature wheel encoders for pulse-based feedback to compute speed and distance traveled. These sensors communicate with the ESP32 through interfaces such as I2C and interrupt-driven GPIO pins, ensuring accurate and synchronized data acquisition. The system processes these inputs to maintain internal state variables such as current position, heading angle, and movement history, which are essential for navigation accuracy. A Manhattan path planning algorithm is implemented to determine optimal movement sequences across the grid, translating target coordinates into step-by-step directional commands. The control outputs are handled through an L298N motor driver module, which receives PWM signals and directional inputs from the ESP32 to drive four DC motors arranged in a differential drive configuration. This setup enables precise control of forward motion, turning, and speed adjustment by independently controlling left and right wheel sets. The architecture also includes real-time telemetry transmission, where sensor readings, encoder counts, yaw values, and system states are periodically sent back to the user interface for monitoring and debugging. The entire system operates within a continuous loop that manages sensor updates, control computations, communication handling, and actuation in real time. The modular separation of sensing, control, communication, and actuation layers ensures scalability, maintainability, and robustness. The architecture demonstrates an efficient integration of hardware and software components, enabling accurate, responsive, and reliable autonomous navigation in structured grid environments.

4. RESULTS AND DISCUSSION

Fig. 2 illustrates the front view of a four-wheeled mobile robot platform integrated with essential hardware components such as the ESP32 microcontroller, L298N motor driver module, MPU6050 IMU sensor, and quadrature encoder interfaces. The configuration presents a symmetric wheel alignment that ensures stable motion and controlled navigation. The front section reflects the integration of control

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circuitry and feedback indicators connected to the processing unit. The internal wiring structure represents the connectivity between sensing, computation, and actuation modules.

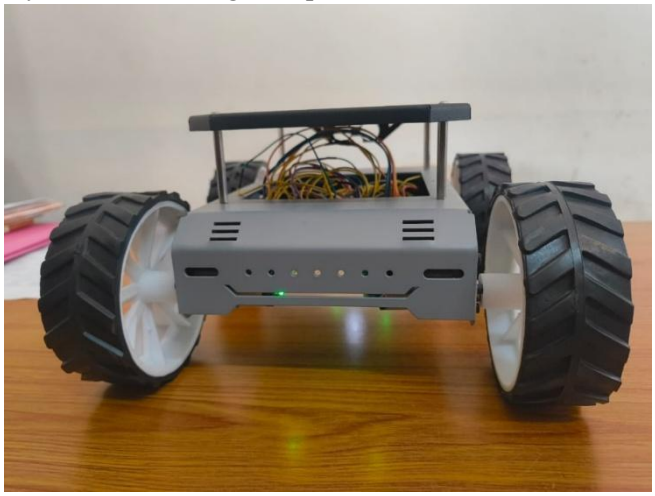


Fig. 2: Front View of a Four-Wheeled Mobile Robot Platform

Fig. 3 depicts the top view of the four-wheeled robot chassis, highlighting the mounting platform used for assembling hardware components including the ESP32 board, motor driver module, battery pack, and sensor units. The arrangement supports efficient spatial distribution of components to maintain system balance and operational stability. The wheel configuration enables differential drive functionality for precise maneuverability. The central region facilitates organized routing of electrical connections and signal pathways.



Fig. 3: Top View of Four-Wheeled Robot Chassis Showing Mounting Plate and Wheel Configuration

Fig. 4 represents the side view of the mobile robot platform, showcasing the placement of hardware elements such as the battery unit, power switch, motor driver module, and DC geared motors. The structural alignment contributes to balanced weight distribution and efficient power management. The elevation illustrates the integration of mechanical and electronic subsystems within a compact framework. The wheel and motor arrangement supports effective torque delivery and smooth locomotion.

Fig. 5 illustrates the experimental setup of the mobile robot operating on a grid-based colored navigation mat, incorporating hardware components such as the ESP32 microcontroller, color sensing unit, motor driver module, and encoder feedback system. The structured grid enables the robot to interpret color inputs and execute navigation decisions accordingly. The integration of sensing and control units

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supports real-time path planning and motion correction. The setup demonstrates the interaction between perception, processing, and actuation modules in a controlled environment.



Fig. 4: Side View of Four-Wheeled Mobile Robot Platform with Power Switch and Integrated Electronics



Fig. 5: Experimental Setup of Mobile Robot on Grid-Based Colored Navigation Mat

5. CONCLUSION

The developed Color-Guided Autonomous Rover achieved reliable indoor navigation by utilizing a cost-efficient multi-sensor fusion framework. The system integrated an ESP32 Microcontroller Unit (MCU) with an MPU6050 Inertial Measurement Unit (IMU) and quadrature encoders to minimize errors typically associated with open-loop motion control. A closed-loop Proportional-Integral-Derivative (PID) controller continuously adjusted motor output, enabling stable straight-line movement and accurate rotational control. To enhance localization reliability, a TCS34725 Red-Green-Blue (RGB) color sensor was incorporated, providing environmental verification at predefined grid points. The use of a dual Inter-Integrated Circuit (I2C) communication architecture allowed efficient separation of high-frequency motion data and sensor inputs, preventing data congestion. The navigation system translated coordinate inputs into controlled movement sequences, ensuring systematic traversal across the grid. Experimental results indicated a noticeable reduction in positional drift compared to traditional

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approaches. Overall, the system offers a scalable and dependable solution for indoor robotic applications in environments where Global Positioning System (GPS) signals are unavailable.

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