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Efficient Battery Management and Workflow Optimization in Warehouse Robotics through Advanced Localization and Communication Systems [†]

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Abstract: This study presents a Warehouse Robot Localization and Communication System prototype to optimize battery management and workflow in warehouses. Autonomous mobile robots equipped with advanced localization and wireless communication technologies coordinate to prevent downtime. When the battery level of the robot drops below a threshold, it communicates with the main computer to request assistance. Another robot then takes over its task, allowing the low-battery robot to reach a charging station. Using an overhead camera module and A* algorithm for optimal pathfinding, robots navigate efficiently. A Python-based user interface enables monitoring and control. This prototype system has the potential for industrial applications with future enhancements.

Keywords: warehouse robotics; battery management; autonomous robots; localization system; pathfinding algorithms; workflow optimization; wireless communication; real-time monitoring

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1. Introduction

In the context of Industry 4.0, Autonomous Guided Vehicles (AGVs) have emerged as self-operating robotic systems, primarily used for material handling and transportation within controlled environments such as warehouses, factories, and distribution centers [1]. These systems operate autonomously, navigating without direct human intervention. AGVs have been widely adopted across various industries due to their versatility in loading options, quiet operation, ease of installation, cost-efficiency, higher throughput, and improved safety. Their implementation reduces labor costs, increases throughput, and improves operational safety. Integrating AGVs into smart manufacturing systems enhances production efficiency by automating logistics workflows, improving response times, and providing greater adaptability to dynamic production demands.

A key technology enabling AGV functionality is color detection, which allows robots to accurately identify and differentiate items, navigate designated paths, and perform quality checks [2]. This capability is achieved through mathematical models known as color spaces, with common models including RGB (Red, Green, Blue), HSV (Hue, Saturation, Value), and YCbCr (Luminance, Blue-Difference, Red-Difference Chrominance) used for image segmentation [3,4]. Image segmentation is crucial for distinguishing objects from their surroundings and can be effectively performed using thresholding in the HSV color space [4,5]. However, optimal HSV values must be adjusted for different situations to ensure accurate detection. OpenCV Python is utilized for shape and color detection due to its accessibility and ease of use [6].

For Unmanned Ground Vehicles (UGVs) in warehouses, localization and mapping are vital for autonomous navigation and obstacle avoidance, contributing to a safer and more efficient environment. Positioning methods are categorized into relative and absolute measurements. Relative positioning employs encoders and gyroscopes, while absolute positioning uses Global Positioning System (GPS) or landmarks [7]. Although GPS is commonly used for AGVs, it struggles with indoor applications due to signal issues; thus, ZigBee has gained popularity for localization due to its higher accuracy. Ceiling lights can serve as effective landmarks for relative positioning but may introduce inaccuracies from unwanted light sources if not filtered out properly. Increasing the number of mobile robots can be costly due to the need for additional camera modules; therefore, a more cost-effective localization method is necessary [7]. UGV systems leverage image processing algorithms to detect obstacles using images from a fixed overhead camera, which is more suitable than geotags in dynamic environments [8].

Path planning algorithms are essential for identifying collision-free routes in environments with obstacles. While static environments require pre-planned solutions, dynamic environments necessitate frequent re-planning to adapt to changing conditions. Most algorithms use grid-based models for path representation, balancing map accuracy with planning time. A* algorithm is particularly effective in finding optimal paths by minimizing cost while avoiding collisions [9,10]. In mobile robot applications, wireless communication protocols are critical for maintaining productivity and mobility. Wireless Fidelity (Wi-Fi)-based systems offer high-speed communication necessary for effective control of UGVs.

Recent advancements in sensor-based technologies in robotics have optimized workflow management and enhanced operational efficiency [11]. Xia Xu et al. conducted a study on a warehouse logistics intelligent positioning information system [12]. It utilizes Zigbee technology and demonstrates significant improvements in data reliability and operational efficiency while minimizing human errors, and optimizing workflow and battery management in warehouse robotics. This highlights the need for implementing advanced technologies to enhance system efficiency and data reliability. Similarly, Zhi Li et al. proposed a warehouse management system based on intelligent robots that optimizes workflow through efficient localization, communication, and dynamic sorting, effectively reducing inventory costs and enhancing automation efficiency [13]. However, their work indicates a lack of discussion on specific challenges faced during implementation, suggesting a need for further exploration of potential improvements in robotic automation within warehouse management systems.

P. Ganesan et al. introduced a microprocessor-based mobile robotic approach for warehouse management that enhances efficiency through advanced localization and communication systems [14]. Yet, their study lacks an in-depth discussion of the challenges encountered during implementation, indicating a gap in understanding the complexities involved in enhancing robot control for efficient warehouse management. Ahmad et al. presented a low-cost indoor localization system using Wi-Fi, Inertial Measurement Unit (IMU) sensors, and wheel encoders to improve inventory management efficiency without incurring additional labor costs [15]. Despite its advantages, the study acknowledges difficulties in accurately tracking warehouse robots and challenges associated with deploying Wi-Fi-based indoor localization systems, emphasizing the need to enhance Wi-Fi accuracy and sensor fusion techniques for better tracking performance.

Likhouzova et al. proposed an EVIN-based solution that integrates robotics and neural networks for optimizing robot paths in warehouse management systems [16]. Their approach aims to reduce collisions and enhance navigation efficiency while cutting production maintenance costs. However, there is a call for further exploration of EVIN technology integration to maximize its potential benefits within warehouse management systems.

While advanced technologies have significantly improved workflow and operational efficiency in warehouse management, a critical gap remains in the integration of automated battery management and real-time task reassignment for AGVs. Conventional manual processes disrupt workflow, increasing downtime and reducing system efficiency. There is a need for an automated solution capable of real-time battery monitoring and intelligent task allocation to minimize operational interruptions and enhance the overall efficiency and reliability of AGV operations in warehouse environments. Addressing this gap can lead to improved productivity and cost reduction.

The objectives of this study are to develop an advanced localization system for precise AGV tracking, design a reliable wireless communication network for real-time data exchange, and implement an integrated battery management system to minimize downtime and enhance productivity. Therefore, this study introduces a prototype of the warehouse robot localization and communication system designed to optimize battery management and maintain an uninterrupted workflow in warehouse environments. The system includes autonomous mobile robots equipped with advanced localization and wireless communication technologies. When a robot currently assigned a task has its battery level drop below a predefined threshold, it communicates with the main computer via Wi-Fi to request assistance. An available robot then adjusts its task, navigating the shortest path to the low-battery robot's location, guided by a webcam system. Then, the low-battery robot proceeds to a charging station after transferring its task to the arrived assisting robot. System operation can be monitored via a Graphical User Interface (GUI) customly designed.

2. Materials and Methods

2.1. System Functionalities

2.1.1. Main System Functionalities

The voltage divider principle was used to measure the voltage of the battery of the UGV, which sends a signal to the transmitter when the battery level reaches the threshold value. A button was designed on the GUI to manually send low battery signals to the control algorithm for testing purposes. The A* algorithm will be implemented to find the shortest route in a working environment, combining the advantages of Dijkstra's algorithm and Best-First Search algorithms. It utilizes a heuristic function to estimate the cost of reaching the destination from each node, guiding the search toward the most promising path while minimizing the number of nodes visited. The optimal path is determined by considering factors such as obstacles and other constraints for guiding an AGV or route optimization. It navigates to the predefined charging point to recharge when the UGV's battery level falls below the threshold and is replaced by another available AGV to continue the workflow. The AGV moves to the parking point awaiting a replacement request from the currently operational AGV ensuring efficient operation and energy conservation.

2.1.2. Mapping Functionality

An overhead webcam captures video input at a low frame rate of 30 FPS to facilitate real-time processing for location identification while minimizing Random Access Memory (RAM) usage, rather than high-speed motion capture. To manage the large matrix from the video input, a 10 × 10 pixel cell is converted into a single data point; if over 50% of the cell contains zeros, it is designated as 0, while if 50% or more contain ones, it is specified as 1, creating a simplified new matrix for further analysis. The edges of identified objects are expanded by two positions around areas marked as zeros to enhance object detection, allowing the UGV to navigate without collisions by treating these expanded areas as obstacles during route planning. The HSV color segmentation method is employed with calibrated threshold values for specific colors, utilizing filters to isolate relevant colors and contours to identify shapes, thereby effectively determining the direction and location of UGVs. coordinates generated by the A* as described above. Letters F, R, S, and E used for forward, 45-degree clockwise rotation, 45-degree counterclockwise rotation, and stop, respectively, indicate UGV movements, ensuring efficient navigation and operation of the UGVs within their environment as shown in Figure 1.

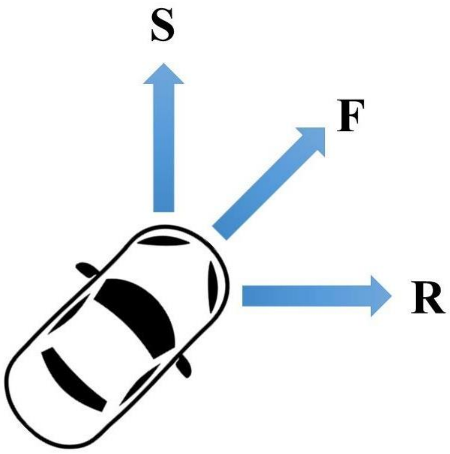


Figure 1. Navigational Path Representation using F (Forward), R (45° Clockwise Rotation), and R (45° Counterclockwise Rotation) Commands.

Figure 2 illustrates the geometric relationship between the corresponding floor area captured in the image and an overhead camera module's Field of View (FOV). The camera module, mounted at a height of 2.5 m, captures an area on the floor which is 2 m wide in the horizontal direction (Horizontal Field of View, HFOV) and 2.2 m in the vertical direction (Vertical Field of View, VFOV). These dimensions correspond to the pixel resolution of the camera module, which is 1920 pixels horizontally and 1080 pixels vertically. By analyzing the camera's HFOV and VFOV, the angles α and β can be determined. The floor area can then be mapped to pixel values based on the camera module's resolution. For instance, each square meter of the floor can be converted into an equivalent number of pixels in both dimensions, allowing for precise detection and analysis of objects within the camera's view. This conversion is critical for accurately tracking movements and events detected by the camera module in a defined space.

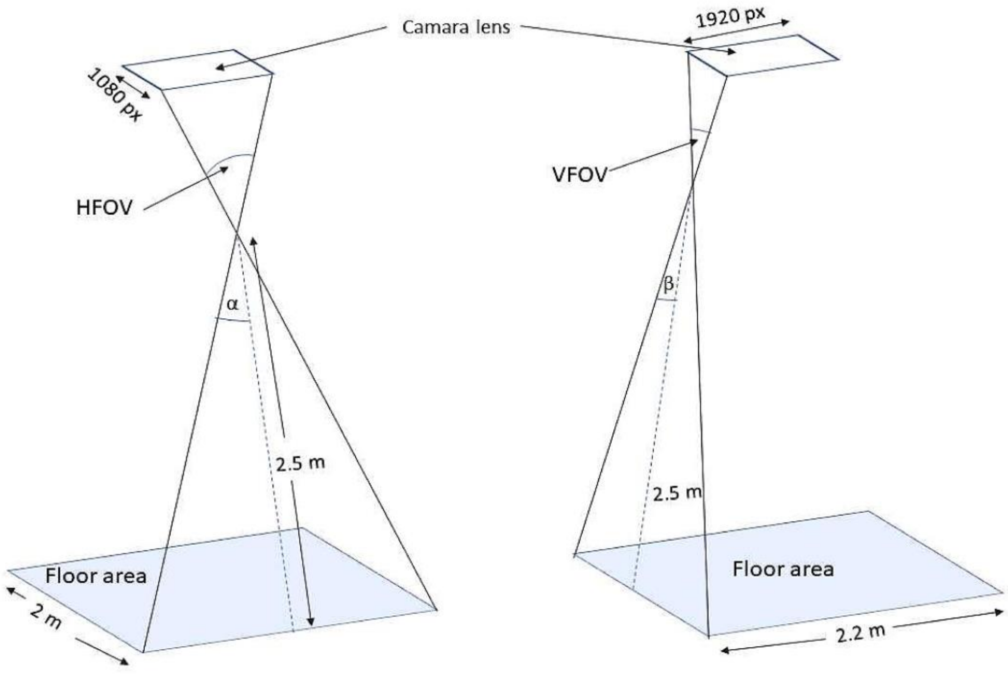


Figure 2. The relationship between the Horizontal Field of View (HFOV) and Vertical Field of View (VFOV) of the camera to the detection floor area.

2.1.3. Communication Functionalities

The main ESP32 board, equipped with a Tensilica Xtensa 32-bit LX6 microprocessor, continuously monitors for incoming signals. Upon receiving a signal, it promptly detects and processes it. The board communicates route letters to all receiver boards using Wi-Fi, facilitating efficient data transmission across the system. Although data is forwarded to all receivers from the main ESP32 board, only the relevant UGV responds to the specific commands associated with that data, ensuring that operations are streamlined and targeted.

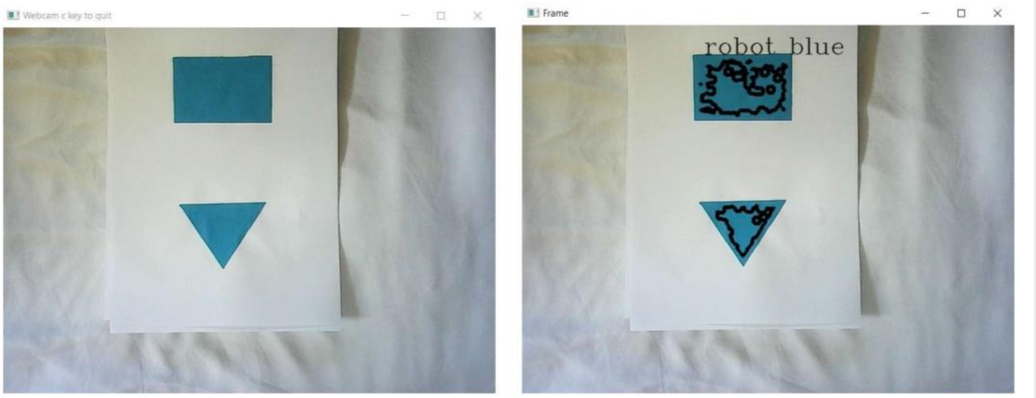
3. Results and Discussion

The threshold values for each color were determined using trackbars created in the GUI, which are essential for real-time object and contour detection through color segmentation algorithms as shown in Figure 3. By utilizing lower and upper HSV values, a specific range of colors can be isolated from the acquired images. Pixels falling below the lower HSV value or above the upper HSV value are excluded from the segmentation process. While fine-tuning these HSV values can yield more accurate results, limitations arise from using a general-purpose webcam for color detection. The specified colors can be filtered out using a generated mask, which is further refined through morphological operations, as illustrated in Figure 3. It is important to note that color calibration is significantly influenced by the lighting conditions in the testing environment; natural lighting can alter the perceived color of objects. Therefore, implementing a controlled artificial lighting method is crucial for achieving accurate color representation. Additionally, various noise factors such as shadows, reflections, and illumination variations, as depicted in Figure 4, must be addressed to ensure clear and usable images.

L-H: 68
L-S: 176
L-V: 107
U-H: 123
U-S: 247
U-V: 245

(a) (b) (c)

Figure 3. Color calibration for system tuning in developed GUI. (**a**) Generated mask for filter out blue color from the captured image; (**b**)Threshold value in the range of 0–255 for different colors is found by changing the Hue Saturation Value (HSV) values on the designed track bar for Autonomous Guided Vehicles (AGV) identification; (**c**) Blue color rectangle detected by generated mask to identify the AGV.



(a) (b)

Figure 4. (**a**) Original image captured by the overhead camera module when lighting conditions are not controlled; (**b**) improper lighting conditions in the testing environment highly affect the color calibration.

The accuracy of color detection in this project is significantly influenced by camera module settings, including white balance, exposure, and saturation. Using a general-purpose webcam often results in color shifts and inaccuracies in the acquired images, making it essential to adjust and optimize the settings of a professional-grade camera module for accurate color representation. Additionally, the selected color space plays a crucial role; thus, the system must be periodically calibrated to account for environmental factors such as natural light to determine optimal threshold values. In this project, the HSV color space is employed for color segmentation tasks, although alternative representations like RGB require different thresholding values. The texture and reflectivity of the mobile robots' chassis also affect color detection, necessitating that color tags be placed on white surfaces for enhanced visibility. Moreover, shadows, occlusions, and lighting direction can further complicate detection accuracy. To improve the FOV, a 180-degree wide-angle lens is proposed; however, barrel and pincushion distortion may affect image analysis. Proper camera module mounting is critical for maximizing FOV and ensuring precise localization, requiring careful consideration of the camera's angle. In a nutshell, employing a higher-resolution imaging device would facilitate easier detection and tracking of mobile robots by providing finer detail.

4. Conclusions

This study developed a Warehouse Robot Localization and Communication System to optimize battery management and enhance workflow efficiency in warehouse environments. The system integrated advanced localization techniques, the A* pathfinding algorithm, and a reliable wireless communication network to ensure the continuous and efficient operation of AGVs. By enabling real-time task reassignment and automated battery monitoring, the prototype minimized downtime and reduced the need for manual intervention. Experimental results demonstrated the effectiveness of the system in maintaining uninterrupted operations and improving productivity. Regular monitoring and adjustment of calibration processes are vital for achieving reliable results in dynamic warehouse environments. With further enhancements, such as incorporating higher resolution camera modules and more robust communication protocols. This system has the potential for practical industrial applications, contributing to the goals of Industry 4.0.

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Abbreviations

AGV	Autonomous Guided Vehicle
UGV	Unmanned Ground Vehicle
GPS	Global Positioning System
Wi-Fi	Wireless Fidelity
IMU	Inertial Measurement Unit
GUI	Graphical User Interface
RAM	Random Access Memory
FOV	Field of View
VFOV	Vertical Field of View

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