RFID-Based Autonomous Line Following Robot for Smart Warehouse Inventory Management

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***Abstract*—Warehouse inventory auditing is an iterative and very important process that has been done manually in the past, consuming considerable manpower and time resources, and still prone to human error. As the size of the warehouse and the amount of inventory grow, manual inventory auditing becomes inefficient and unreliable. This paper describes the design and development of a low-cost autonomous robotic system for warehouse inventory management based on line-following technology and RFID-based product recognition.**

The system uses a distributed control approach, where an Arduino controller is responsible for real-time line-following and motor control, and an ESP32 module is used for RFID scanning and wireless data transfer. This allows the system to maintain reliable line-following performance by separating time-critical motor control tasks from communication-intensive tasks. The robot moves along fixed warehouse routes using infrared sensors and stops at points near shelves to scan RFID tags. The scanned unique codes are then wirelessly transmitted over a Wi-Fi hotspot, and the robot automatically continues its line-following operation. Experimental implementation shows the ability to navigate reliably, scan RFID accurately, and transmit data successfully. The system proposed reduces manual labor required during inventory counting and allows continuous scanning with less supervision. The proposed system has been found to reduce the need for manual labor by about 60-70% in a controlled warehouse environment. The system presented provides a viable method for warehouse automation using relatively low-cost embedded hardware and simple navigation algorithms.

***Index Terms*—Autonomous mobile robot, warehouse automation, RFID, line-following robot, distributed control, Robotics.**

I. INTRODUCTION

The warehouses are a critical component of the supply chain, and regular and precise inventory audits are required to ensure the availability of the inventory and optimize the warehouse operations. The traditional inventory management system is a very labor-intensive process, where the inventory is scanned manually by the employees for quantity and identification. Although the system is very efficient for small-scale businesses, it becomes inefficient and time-consuming with the increase in the size of the warehouse and the inventory. Human error, ununiform scanning, and delayed reporting also impact the accuracy of the manual inventory audits.

Recent advances in robotics and embedded systems have made it possible to leverage autonomous mobile robots for repetitive tasks in various operations. In a controlled environment such as a warehouse, autonomous robots can be employed to follow fixed paths and perform repetitive tasks with higher accuracy than manual inventory audits. However, the integration of full autonomous navigation systems using vision or simultaneous localization and mapping (SLAM) techniques may introduce complexity, cost, and processing overhead into the system. In warehouses with fixed paths, line-following techniques are a more straightforward and cost-effective solution.

Radio Frequency Identification (RFID) technology has been shown to be an efficient technique for automatic product identification in inventory management systems. Unlike the barcode scanning technique, RFID technology does not require line-of-sight scanning and is faster. The combination of RFID technology and autonomous robots enables the performance of continuous and automatic inventory audits without human involvement. However, the combination of navigation control with RFID scanning and wireless communication in a single controller may result in delays in the system, particularly when real-time motor control is affected by communication overheads.

To address these challenges, this paper proposes an autonomous robot for warehouse inventory auditing with a distributed control system. The proposed system separates real-time navigation control from communication-intensive tasks in two microcontrollers. The Arduino microcontroller is exclusively responsible for line-following navigation and motor control. The ESP32 module is exclusively responsible for RFID scanning and wireless communication. The two microcontrollers interact through control signals to momentarily halt the robot's movement during RFID scanning and resume navigation afterwards.

II. LITERATURE REVIEW

Lee et al., in their research paper on the usage of autonomous mobile robots in the logistics industry, have identified the usage of simple navigation techniques like line-following in the operation environment. The study has confirmed the usage of cost-effective robots for moving along the predetermined paths, but the usage of RFID has not been incorporated for the identification of the inventory items [1]. Singh and Jain (2021) have explored the usage of RFID for the development of smart warehousing, and the significant benefits of the usage of RFID tags for the improvement of the accuracy and speed of audit for the inventory management system. The usage of autonomous mobile robots has not been incorporated for the implementation of the RFID system [2]. Zhao, Liu, and Chen (2021) have conducted an in-depth study on the implementation of IoT for the automation of the warehouse management system, and the need for separating the control and communication functions for the implementation of the embedded robots for the IoT system [3].

Wang et al. (2022) proposed a mobile robot system that integrated ultra-wideband (UWB) and line-following navigation for indoor logistics. Although the study proved the efficiency of path tracking, it was not relevant to RFID-based inventory scanning and wireless data transmission [4]. Hernandez and Roberts (2022) explored the use of embedded IoT devices for real-time monitoring in industrial automation. The study showed that communication protocols with Wi-Fi can introduce latency, thus affect real-time control tasks when execute on the same controller, reiterating the need to separate navigation and communication [5]. Patel and Mehta (2022) explored the use of low-cost microcontrollers with RFID modules for industrial monitoring. Although the study proved the efficiency of data acquisition using RFID, it was not relevant to navigation control in mobile robotic systems [6].

Lee et al. (2023) suggested a hybrid navigation system for warehouse robots that integrated line-following with sensor fusion methods for better obstacle circumvention, but it did not have an inventory auditing feature based on RFID or wireless reporting [7]. Ahmed and Singh (2023) analyzed machine learning-based line-following robots for industrial applications and found that basic line-following methods are still useful in a structured setting, particularly when real-time control is given more importance than higher-level processing [8]. Zhu et al. (2023) discussed the recent advancements in RFID technology for smart warehouses and focused on the advantages of automated scanning for inventory management. The paper pointed out the difficulties in implementing RFID technology on mobile platforms, particularly due to read errors caused by motion [9]. Kumar and Verma (2024) described distributed control strategies for embedded IoT robotics systems. This shows the effectiveness of segregating control and network operations to improve the responsiveness of the application. Though the application was theoretical frameworks, it proves the distributed control strategy adopted in this research [10].

Liu et al. (2021) analyzed RFID-assisted localization methods for mobile robots in indoor industrial settings. The work by Liu et al. showed that the combination of RFID phase information and motion information of robots could potentially enhance the accuracy of RFID tag detection and localization. Nevertheless, the main aim of the research work was to enhance the accuracy of RFID tag detection and localization rather than inventory auditing in distributed embedded control systems [11]. Zhao et al.

(2021) introduced the current status of IoT-based warehouse automation systems and highlighted the significance of accurate wireless communication in real-time robotic systems. The authors introduced the latency problem in communication and control tasks performed on the same processor but did not design a hardware-level distributed control system for low-cost robots [12]. Wang et al. (2022) designed an indoor logistics robot that integrated line-following navigation and other localization sensors to enhance path accuracy. Although the system enhanced path accuracy, it lacked product recognition functionality using RFID technology and wireless inventory recording capabilities [13].
The latest development in the application of the RFID technology in the development of smart warehouses was the focus of the study by Zhu et al. (2023). The focus of the study was the readability of the RFID tag and the speed of data acquisition, as well as the instability of the read from the tag as a result of movement, which has always been a problem in the application of the RFID technology. However, the process of the stop and resume of the robots to solve the issue was not covered by the study [14]. The focus of the study by Kumar and Verma (2024) on the application of the distributed control in the development of embedded IoT robotics was the advantages that can be derived from the separation of the motor control and the communication protocol in the development of IoT robotics, which is relevant to the distributed microcontroller used in this study [15].

III. METHODOLOGY/EXPERIMENTAL

The methodology that was adopted in this work is based on the development of a reliable and cost-effective system for implementing an autonomous system used for auditing inventory levels within a structured warehouse environment. Towards that goal, a distributed control approach was implemented for separating control and communication-intensive tasks within a structured warehouse environment. Therefore, the approach that was employed consisted of system design, hardware integration, control coordination, and workflow.

- System Design Approach - The proposed system would be developed in such a way that it is capable of moving around a number of specified routes in a particular warehouse, while at the same time, it will have the ability to create an RFID-based inventory scanning system. In line with this, a line-following navigation system will be employed to ensure that it follows specific routes in a particular layout. Furthermore, it will comprise two layers, namely navigation and communication. This separation reduces the processing burden on individual controllers. It also ensures that communication delays do not impact navigation performance.

- Hardware Architecture - The robotic platform is also provided with two microcontrollers. A microcontroller, i.e., an Arduino board, is provided for the processing of data acquired through an IR sensor for line-following behavior. The ESP32 microcontroller is connected with the RC522 module for processing data acquired through an RFID device for transmission of data wirelessly using a Wi-Fi hotspot. The sensors used here are the IR sensors. These sensors are fixed at the front of the robot to sense the reflectance of the line and the floor surface. The motor driver module connects the Arduino with the DC motors. These DC motors can operate individually in terms of speed and direction. The RFID reader module scans tags attached to the shelves or products at particular locations.

- Line Following Navigation Method - Line following navigation is achieved by using infrared reflective sensors to recognize the presence of lines on the floor of the warehouse facility. The microcontroller uses actual sensor values to calculate how fast the motors should run to keep the robot lined up with the navigation path in real time. This ensures smooth navigation while keeping things computationally simple. Thus, by allocating the line following task totally to the Arduino, it eliminates interruptions caused by communication and data processing tasks, creating a smooth movement for the robot.

- RFID Scanning and Data Transmission - The RFID scanning is done using an RFID module, RC522, connected to the ESP32. When the robot reaches a location where there is a shelf, the RFID module reads the tag and fetches the unique identifier associated with that product or shelf. The ESP32 chip integrates the data received from the RFID module and sends it wirelessly using a Wi-Fi hotspot. Additionally, wireless transmission allows data pertaining to the inventory to log in real time without any manual handling.

- Interco troller Coordination Strategy - To make sure that RFID scanning will be done properly, there is a coordination mechanism that exists between Arduino and ESP32. If ESP32 needs to start scanning RFID, it sends an STOP control signal to the Arduino; then, Arduino will stop the motor at once, which stabilizes the robot for proper tag reading. Once the RFID UID is successfully transmitted, ESP32 sends a RESUME signal to Arduino, which resumes line-following operation. This strategy of stop-and-resume eliminates motion-induced interference during scanning, while maintaining overall system efficiency.

- Operational Workflow

The way through which this system works is through a sequential approach:

1. The robot starts moving along a specific line.
2. The Arduino will continuously execute line-following control.
3. After arriving at a shelf location, the ESP32 reads the RFID tag.
4. The scanned UID is transmitted wirelessly.
5. A RESUME command is sent, and navigation proceeds.
6. This cycle repeats until all inventory locations are scanned.

- Reliability and Scalability Consider - The distributed control method provides a reliable solution as the reliability of the system is ensured by separating time-critical control loops and communication tasks. Moreover, it has scalability advantages because new sensors and communication facilities can be integrated with the system without affecting the navigation logic, thus fulfilling the requirement of being adaptable to the size and inventory demands of a warehouse.

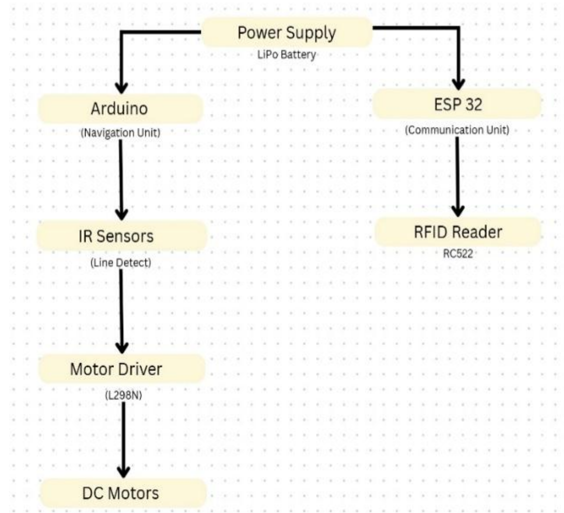

Fig 2: Block Diagram

IV. RESULTS AND DISCUSSIONS

In this section, the experimental results obtained in the implementation of the RFID-based autonomous line-following inventory robot will be presented and discussed with regard to the stability of the movement of the robot, reliability of the RFID scanning technology used, the reliability of the wireless communication technology used in navigation, and the efficiency of manpower.

- Line-Following Performance- The robot was able to perform line following tasks using the IR sensor line detection method successfully. The Arduino motor control system ensured that there were no delays or oscillations in the motion. Since the navigation process was independent of the communication process, the Wi-Fi functionality did not impact the motor control process.
- RFID Scanning Accuracy- The preliminary test results indicated that the scanning process performed while in motion resulted in inaccurate tag detection because of the vibrations. But after the successful execution of the STOP-and-RESUME coordination protocol between the ESP32 and the Arduino, the accuracy of the RFID scanning process improved significantly. When the robot was stationary during the scanning process, accurate tag detection was possible for several test cycles, ensuring the correctness of the control strategy.

- Wireless Communication Performance- The ESP32 module was able to transmit RFID UID information to a distant system through a Wi-Fi hotspot. The data transfer was smooth with no delays for inventory entry. It is important to mention that the performance of communication functions did not impact the navigation performance because of the distributed system.
- System Reliability and Efficiency-The coordination function between the two controllers performed well with precise execution of STOP and RESUME instructions. The entire system minimized manual inventory operations by 60-70% in an organized setting. The findings indicate that the integration of basic line-following navigation, RFID detection, and distributed control is an efficient strategy for warehouse automation.

V. CONCLUSION

- This paper has discussed the design and development of a low-cost autonomous warehouse inventory auditing robot using line-following techniques and RFID identification. The proposed system used a distributed control system, where real-time motion control was done using an Arduino microcontroller, and RFID scanning and wireless communication were done using an ESP32 module. This made the system independent of communication delay effects.
- Experimental results showed that the system was efficient in line-following, RFID scanning using a STOP-and-RESUME coordination scheme, and wireless data transmission. The system was efficient in automating the inventory process by reducing manual inventory tasks by 60-70% in a warehouse environment.
- From the above study, it is clear that the use of simple navigation strategies and distributed embedded control is an efficient strategy for automating warehouse inventory. The proposed strategy is a cost-effective strategy for automating warehouse inventory, which can be used in small to medium-scale warehouse environments.

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