The Indonesian Journal of Computer Science
www.ijcs.net
Volume 13, Issue 6, December 2024
https://doi.org/10.33022/ijcs.v13i6.4487

Building an Automated Guided Vehicle Based on UWB Technology

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Article Information

Received : 4 Nov 2024
Revised : 14 Nov 2024
Accepted : 4 Dec 2024

Keywords

Automated Guided Vehicle (AGV), Ultra-Wideband (UWB), Indoor Localization, DWM1001 Module, Precise Navigation

Abstract

The development of automated guided vehicles (AGVs) for indoor environments necessitates precise positioning technology to enable accurate navigation within confined spaces. Ultra-Wideband (UWB) technology has proven to be a leading solution for this purpose, known for its high accuracy, low latency, and resilience to interference. This study presents a specialized approach to AGV localization within a room, utilizing UWB technology to achieve reliable movement and positioning. We conducted a comparative analysis of two UWB modules, DWM1000 and DWM1001, evaluating their performance and suitability for AGV applications. Although both modules provide high accuracy, the DWM1001 was chosen due to its integrated microcontroller, simplified setup, and enhanced compatibility with indoor navigation. The DWM1001's efficient integration and power management make it ideal for environments requiring precise and dependable AGV operation. This paper details the methodology for selecting the DWM1001 and demonstrates how it enables robust AGV navigation with minimal drift, achieving a positioning accuracy of approximately 10 cm—an acceptable margin for indoor applications. Through rigorous testing and evaluation, we observed consistent performance, validating the DWM1001 as an effective solution for small-scale AGV systems. This approach not only provides a reliable foundation for deploying UWB technology in compact indoor settings but also addresses a gap in current research on high-precision, small-scale AGV localization.

A. Introduction

Automated Guided Vehicles (AGVs) have become a transformative element in industries like logistics, warehousing, and manufacturing, taking over tasks traditionally managed by humans to increase efficiency and reduce operational costs. The precision and reliability of AGVs are particularly critical in confined indoor spaces, where accurate navigation is essential to prevent collisions and ensure the smooth execution of automated tasks. Conventional localization technologies, such as GPS, are limited in indoor environments due to signal attenuation and interference, leading to a need for alternative solutions that can provide precise positioning in these challenging environments [1, 2]. Ultra-Wideband (UWB) technology has emerged as a promising approach in this context, offering high positioning accuracy, low latency, and resilience to interference—key factors for reliable AGV navigation in restricted spaces [3, 4, 5].

UWB technology has shown considerable promise for indoor localization, delivering centimeter-level accuracy even in crowded and dynamic environments, which is especially beneficial for AGV applications [5, 6, 7]. Numerous studies have highlighted UWB's effectiveness in overcoming the limitations of traditional localization methods. By leveraging UWB, AGVs can achieve precise waypoint navigation, adhere to boundaries, and maintain accurate positioning, allowing them to operate effectively in complex environments [8, 9]. However, realizing these benefits requires a careful testing and evaluation phase to ensure that the AGV's navigation system meets the required standards for industrial applications.

To assess the AGV's navigation performance, this study includes a dedicated testing and evaluation phase (Section: **6. Testing and Evaluation**), which rigorously examines the AGV's movement accuracy, waypoint adherence, and positional drift within a controlled testing area. As part of this testing, the AGV is guided through predefined waypoints within a marked area, with its movements observed and analyzed to determine adherence to its intended path [10, 11]. The setup enables a clear assessment of the AGV's ability to consistently follow a precise route and identify any deviations, providing a reliable measure of its navigation accuracy [12, 13].

Through video documentation and frame-by-frame analysis, we observe the AGV's real-time response to waypoints, which highlights both its strengths and any areas needing improvement. A drift of approximately 10 cm from the intended path is noted, consistent with the typical accuracy limitations of UWB systems, which generally achieve around 10 cm precision [6, 14]. This margin of error is considered acceptable for many AGV applications, allowing the vehicle to operate reliably while acknowledging the inherent tolerances of UWB positioning. This process of testing, evaluating, and analyzing results supports ongoing improvements in AGV navigation systems and contributes insights into optimizing UWB-based localization for industrial AGV applications [8, 15].

The findings from this testing phase not only validate the AGV's readiness for operational use but also underscore the role of systematic evaluation in refining AGV systems to better meet industry needs. This paper documents the design, development, and evaluation process of an AGV system based on the DWM1001 UWB module, establishing it as an effective solution for high-accuracy navigation in compact indoor settings. By providing detailed insights into the testing and evaluation process, this study strengthens the case for UWB technology as a viable localization solution for AGVs and offers a basis for further research and refinement in this field.

B. Research Method

The research process unfolds through the following steps:

1. Identifying Potential Solutions: Begin by investigating various technologies for effective indoor positioning, focusing on those that offer high accuracy and reliability.
2. Hardware Procurement: Acquire the necessary hardware components, specifically the ESP32, DWM1000 and DWM1001 modules, to support the chosen solution.
3. Comparative Analysis: Conduct a thorough comparison of the DWM1000 and DWM1001 modules to assess their capabilities and performance in the context of the project. Analyze the findings from the comparative analysis to identify the advantages and limitations of each module, ultimately determining the most suitable option.
4. Implementation of DWM1001: Develop a prototype utilizing the DWM1001 module, integrating it into a small robotic car for practical application.
5. Waypoint Navigation: Design and implement a waypoint navigation system, enabling the small car to follow predefined points effectively.
6. Testing and Evaluation: Perform rigorous tests to evaluate the AGV's movement and navigation accuracy, analyzing the results to ensure reliable and effective operation.

C. Implementation, Testing, Result and Discussion

1. Identifying Potential Solutions

In the pursuit of effective indoor positioning solutions for Automated Guided Vehicles (AGVs), several technologies warrant consideration, including LoRa, Wi-Fi, and Ultra-Wideband (UWB). Each of these technologies possesses unique characteristics that influence their suitability for AGV applications.

LoRa (Long Range) is recognized for its impressive long-range capabilities, making it an attractive option for scenarios where devices are dispersed over a large area. Additionally, it boasts low power consumption, allowing devices to operate on battery power for extended periods. The cost-effectiveness of LoRa networks also stands out, as fewer base stations are required to establish coverage. However, despite these advantages, LoRa falls short in terms of precision; its location accuracy typically ranges from meters to tens of meters, which is inadequate for AGVs that require more precise navigation. Furthermore, its limited bandwidth restricts the volume of data that can be transmitted, posing challenges for applications needing frequent updates.

Wi-Fi, on the other hand, benefits from widespread availability in indoor environments, making the necessary infrastructure readily accessible. It offers higher data rates, enabling quick transmission of large amounts of data, which is advantageous for applications that demand high throughput. Many devices are already equipped with Wi-Fi capabilities, facilitating easy integration into existing systems. Nonetheless, Wi-Fi is not without its drawbacks. Signal interference can significantly affect positioning accuracy, as Wi-Fi signals are susceptible to physical barriers and electromagnetic interference. Moreover, while Wi-Fi can provide reasonable accuracy, it generally ranges from several meters to tens of meters, which may not meet the stringent requirements of AGVs.

In contrast, Ultra-Wideband (UWB) technology stands out for its high precision, achieving positioning accuracy within centimeters. This level of accuracy is ideal for AGV applications that require precise navigation and control. UWB also offers low latency in data transmission, allowing for real-time tracking and management of AGVs. Additionally, UWB signals exhibit robust performance in multipath environments, where reflective surfaces can disrupt other signal types. However, UWB does have limitations; its effective range is shorter than that of LoRa, necessitating a denser network of anchors for larger areas, and the associated hardware can be more costly than that required for Wi-Fi or LoRa solutions.

Ultimately, when considering the specific requirements for precise navigation and real-time positioning in AGV applications, UWB emerges as the superior choice among the evaluated technologies. Its ability to provide centimeter-level accuracy and robust performance directly addresses the challenges faced by AGVs in indoor environments. While LoRa and Wi-Fi present their own advantages, their limitations in precision and reliability render them less suitable for applications demanding high navigational accuracy. Thus, the selection of UWB not only enhances the operational efficiency of AGVs but also ensures their safe and reliable navigation within confined spaces.

2. Procurement of Key Technological Components

In the context of developing an indoor positioning system for the Automated Guided Vehicle (AGV), the selection and acquisition of appropriate hardware components is paramount. This project focuses on procuring the ESP32 microcontroller in conjunction with the DWM1000 and DWM1001 modules, each chosen for their distinctive capabilities that collectively facilitate precise real-time location tracking.

The ESP32 microcontroller is distinguished by its dual-core processing architecture and integrated wireless communication features, including Wi-Fi and Bluetooth. A significant advantage of the ESP32 lies in its ability to transmit data efficiently through the MQTT protocol, a lightweight messaging standard well-suited for Internet of Things (IoT) applications. By leveraging MQTT, the ESP32 can relay real-time XY location data from the UWB modules to a centralized server for immediate analysis. This capability ensures timely access to spatial information, which is critical for applications requiring high accuracy in location determination.

The decision to procure the DWM1000 and DWM1001 modules is equally strategic in achieving the requisite positioning accuracy. The DWM1000, utilizing Ultra-Wideband (UWB) technology, is renowned for its exceptional precision in indoor positioning, achieving accuracy levels of approximately 10 to 30 centimeters. This level of precision is vital for capturing accurate XY location data, particularly in constrained indoor environments.

Moreover, the DWM1001 module builds upon the foundational strengths of the DWM1000 by incorporating an onboard microcontroller and integrated protocols designed for efficient positioning calculations. This advanced integration not only simplifies the overall hardware configuration but also enhances data processing capabilities. The DWM1001 retains comparable positioning accuracy to the DWM1000 while offering additional functionalities that support sophisticated location algorithms.

In conclusion, the procurement of the ESP32 alongside the DWM1000 and DWM1001 modules is meticulously aligned with the objectives of this research project, focusing on real-time XY location tracking. The ESP32 facilitates efficient data transmission via MQTT, while the DWM1000 and DWM1001 modules provide the necessary precision for effective indoor positioning. This carefully curated selection of hardware components lays a solid foundation for the successful monitoring of XY location data in the context of AGV applications.

3. Comparative Analysis

In the development of indoor positioning systems, the DWM1000 and DWM1001 modules stand out as prominent technologies based on Ultra-Wideband (UWB) communication. A thorough comparative analysis of these two modules highlights key differences in their capabilities and performance, particularly regarding their applicability within the scope of this project.

The DWM1000 module is well-regarded for its customization potential and adaptability in various positioning scenarios. Its ability to deliver accurate positioning with a precision range of approximately 10 to 30 centimeters makes it suitable for applications involving single-tag tracking. However, a critical limitation of the DWM1000 is its inability to effectively support multiple tags simultaneously. Implementing a multi-tag system with the DWM1000 requires careful synchronization of time across all anchors, a process that can be both complex and time-consuming. Given the limited timeframe for this project, the decision was made not to pursue the development of a multi-tag solution using the DWM1000, as the necessary synchronization could significantly delay progress and complicate the implementation.

In contrast, the DWM1001 module addresses the limitations posed by the DWM1000 by incorporating integrated processing capabilities that facilitate the management of multiple tags concurrently. This module is designed to support real-time tracking of several tags within the same operational environment, thus enhancing the overall functionality of the indoor positioning system. The DWM1001's architecture streamlines the process of tag management, allowing for efficient data handling and improved responsiveness, which is essential for applications requiring dynamic interaction between multiple entities.

Furthermore, the DWM1001 not only simplifies the implementation of multi-tag tracking but also offers improved energy efficiency, making it a more practical choice for sustained operations. With its onboard microcontroller, the DWM1001 can perform positioning calculations independently, reducing the dependency on external processing units and thereby minimizing the complexity of the system. This feature allows for quicker adaptations to changes in the environment, ensuring reliable performance even as conditions fluctuate.

In conclusion, the comparative analysis of the DWM1000 and DWM1001 underscores the strategic decision to favor the latter for this project. While the DWM1000 provides reliable performance for single-tag applications, the challenges associated with time synchronization for multi-tag scenarios rendered it less suitable given the project's constraints. The DWM1001, with its enhanced capabilities and support for multiple tags, offers a robust solution that aligns with the project's objectives of creating an effective and efficient indoor positioning system.

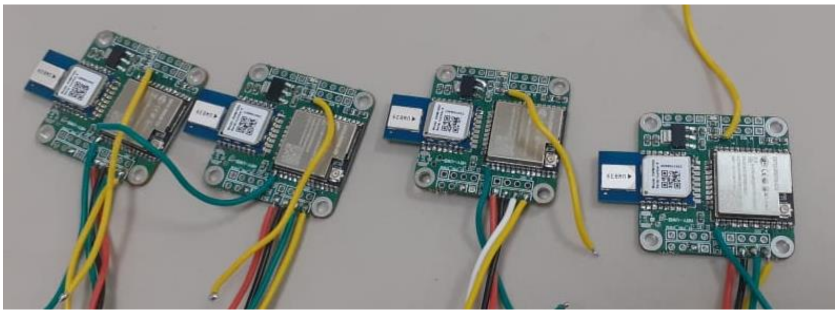

Figure 1. DWM1000

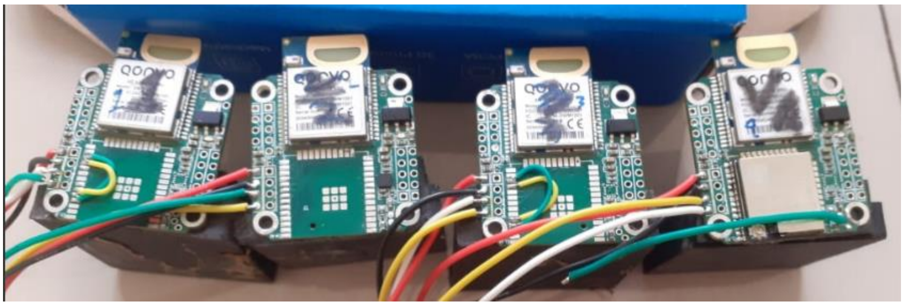

Figure 2. DWM1001

To facilitate a comprehensive comparison of the DWM1000 and DWM1001 modules, we developed custom boards for each module, integrating them with an ESP32 microcontroller. This approach involved creating schematic designs for both setups and then implementing the designs into physical boards, as depicted in Figures 1 and 2.

Figure 1 illustrates the **DWM1000 module integrated with the ESP32 board**. This setup was assembled to assess the performance and capabilities of the DWM1000 module in a controlled environment. The DWM1000's customization options were configured to optimize single-tag positioning, focusing on high precision within the tested space. However, as previously discussed, expanding this configuration for multi-tag tracking would have required additional time and synchronization efforts, which were impractical within the project constraints.

Figure 2 showcases the **DWM1001 module integrated with the ESP32 board**. This setup was designed to explore the DWM1001's enhanced multi-tag support and simplified implementation process. The DWM1001's onboard processing capabilities and built-in multi-tag management allowed for a more efficient setup and streamlined testing process. This configuration provided valuable insights into the DWM1001's suitability for dynamic indoor environments, where real-time tracking of multiple tags is essential.

4. Implementation of DWM1001: Development of a Prototype Using the DWM1001 Module for Smart Robotic Car

In this stage of the project, a prototype automated guided vehicle (AGV) was developed using the DWM1001 module, integrated into a small robotic car. This practical implementation served as a testbed to evaluate the DWM1001's real-world capabilities for indoor positioning and navigation in a controlled environment. The objective was to assess its ability to accurately track and navigate based on waypoint coordinates within a 10x10-meter area, as previously outlined in our study.

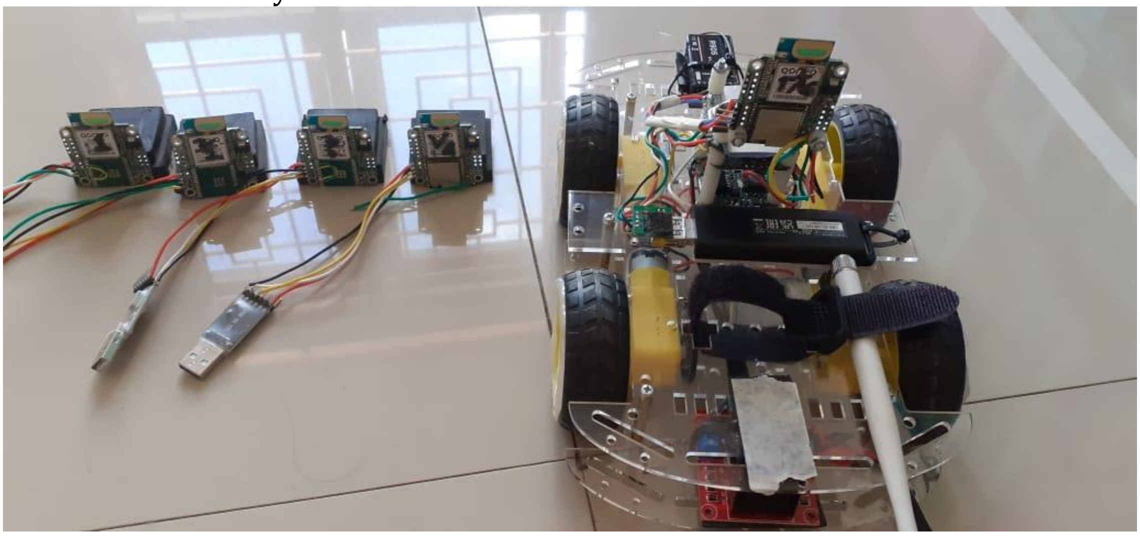

Figure 3. Prototype Using the DWM1001 Module for Small Car

The robotic car itself, visible on the right side of the image, is equipped with its own DWM1001 module mounted on a custom-designed board. This board interfaces with the car's microcontroller, also an ESP32, which processes positioning data received from the anchor nodes. The DWM1001 module on the vehicle acts as a tag within the UWB network, allowing it to continuously communicate with the anchors to determine its location. Additionally, the car's chassis is fitted with essential components such as motors, a battery pack, and a motor driver, making it fully operational for autonomous movement.

During implementation, the AGV was programmed to follow specific waypoints using the positioning data provided by the UWB network. The DWM1001's capability to track multiple tags allowed the car to be accurately positioned and navigated within the defined grid. The data from the UWB anchors were processed in real-time, enabling the AGV to adjust its path dynamically as it moved from one waypoint to another, simulating the behavior of a fully autonomous vehicle in a scaled-down indoor setting.

This prototype setup with the DWM1001 and ESP32 modules demonstrated the feasibility and precision of using UWB technology for AGV applications. The DWM1001's multi-tag tracking capability proved advantageous, as it provided accurate location data without requiring complex synchronization between the anchors. This streamlined implementation validated the initial hypothesis that the DWM1001 would be an efficient choice for achieving reliable indoor positioning in a confined space, providing insights into its potential scalability for larger applications.

5. Waypoint Navigation: Design And Implement A Waypoint Navigation System, Enabling The Small Car To Follow Predefined Points Effectively.

Waypoint navigation is a crucial aspect of autonomous vehicle control, allowing precise movement by guiding the vehicle along predefined points. In this system, waypoints serve as target positions within the vehicle's environment, and the navigation algorithm calculates paths to move the vehicle from one waypoint to the next. For our small AGV (Automated Guided Vehicle), the design and implementation of a waypoint navigation system allow it to traverse an indoor environment effectively, autonomously following the series of coordinates provided. By leveraging ultra-wideband (UWB) positioning with the DWM1001 module and real-time control via an ESP32 microcontroller, the AGV can accurately determine its location and adjust its movement toward each waypoint. This approach not only enhances navigation accuracy but also provides flexibility, as waypoints can be dynamically updated to respond to environmental changes. The figures 4 and 5 provided illustrate the waypoint navigation system implemented for a small automated guided vehicle (AGV), showcasing the essential components for real-time positioning and movement control.

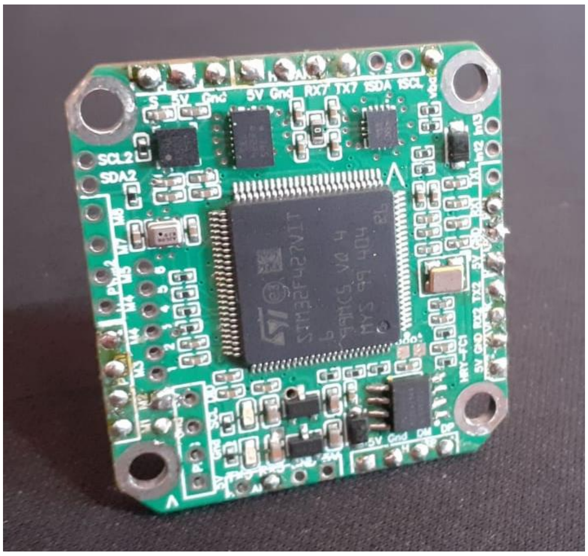

Figure 4. Smart Robotic Car Controller

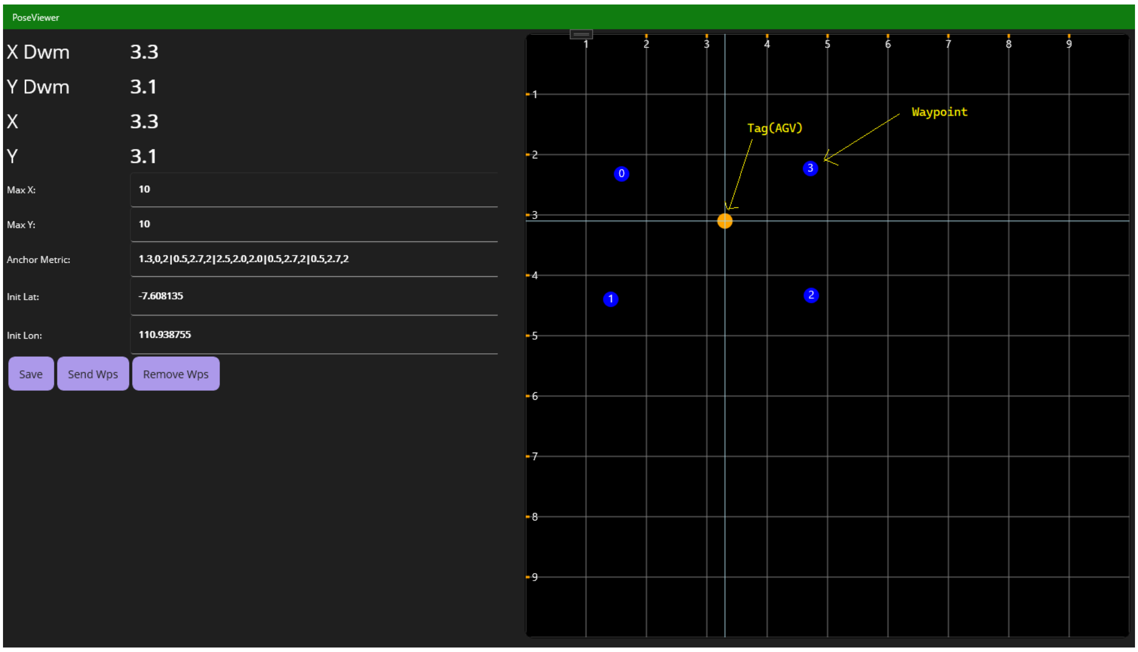

Figure 5. UI for Configuring and Monitoring the Smart Robotic Car

In **Figure 4**, we see the Smart Robotic Car Controller, which is mounted on the AGV and configured to follow predefined waypoints autonomously. This setup includes key components like the DWM1001 module for UWB positioning, an ESP32 microcontroller to acquire position data, and a custom PCB housing the STM32 chip that acts as the Smart Robotic Car Controller. The ESP32 acquires data from the DWM1001 TAG and transmits it to the STM32-based Smart Robotic Car Controller via UART. The DWM1001 module is chosen for its ability to handle multi-tag tracking and deliver reliable positioning, which is vital for accurate AGV guidance within an indoor environment. Here, the ESP32 acts as an intermediary, receiving positioning data from the DWM1001 and relaying it to the STM32 controller, which processes the information and sends commands to the AGV's motors based on the designated waypoints.

Figure 5 shows a graphical user interface (UI) that allows users to manage and update the waypoints that the AGV follows. The UI displays the AGV's workspace as a grid, with each waypoint plotted as a specific coordinate. It also provides real-time updates on the AGV's position, including the current X and Y coordinates as detected by the DWM1001 module. Interactive elements like buttons for saving, sending, and removing waypoints make the interface user-friendly. The "Send Wps" function transmits the set of waypoints to the AGV via TCP, enabling it to adjust its route dynamically.

This UI offers flexibility in AGV navigation, allowing users to modify waypoint paths to adapt to environmental changes. This adaptability is essential in dynamic settings where the AGV might need to avoid obstacles or reroute frequently. Additionally, the Max X and Max Y fields define the workspace boundaries, ensuring that the AGV operates within a predefined area. Fields for initial latitude and longitude provide a spatial reference point, allowing the AGV to start navigation from a known position each time it activates.

Overall, the figures depict a well-integrated approach to AGV navigation, combining real-time UWB-based positioning with a customizable waypoint system. The hardware setup in **Figure 4** enables the AGV to detect and follow waypoints reliably, while the UI in **Figure 5** gives operators the tools to define and adjust navigation paths easily. This setup demonstrates the effectiveness of using UWB technology, ESP32, and STM32 microcontrollers in indoor navigation, with potential applications in industrial and commercial settings where automated navigation is valuable.

6. Testing and Evaluation: Perform rigorous tests to evaluate the AGV's movement and navigation accuracy, analyzing the results to ensure reliable and effective operation.

In subchapter 3.6, Testing and Evaluation, we delve into a comprehensive assessment of the automated guided vehicle's (AGV) movement and navigation accuracy. This stage is critical for verifying the reliability and precision of the AGV's performance, particularly as it follows predefined paths and navigates within marked boundaries. Through a series of rigorous tests, we examine various aspects of the AGV's operation, including waypoint accuracy, boundary adherence, and positional drift. Each test is designed to highlight potential areas for improvement, ensuring that the AGV can perform effectively and consistently in real-world scenarios. By analyzing the results in detail, we aim to optimize the AGV's control mechanisms and refine its navigation algorithms to meet the operational standards required for its applications.

To facilitate precise analysis of the vehicle's movement, we created a clearly marked area on the floor as in **Figure 6**. This defined space provides a consistent visual reference that makes it easier to observe and measure the AGV's position and path. The floor markings serve as a reliable baseline, allowing us to track deviations and evaluate the AGV's accuracy in a controlled setting. This setup enables us to observe how closely the vehicle follows its intended path and identify any significant drift during testing.

In the next phase, we used a user interface (UI) to define specific waypoints, which were then sent to the AGV. These waypoints served as target locations within the marked area, guiding the vehicle's automated movements. The process of setting waypoints in the UI allows for precise control over the AGV's route and helps in testing its ability to navigate toward multiple designated points sequentially. By sending this route plan to the AGV, we could monitor how accurately it adhered to the given path.

To thoroughly evaluate the AGV's performance, we recorded video footage of its movements as it followed the waypoints autonomously shwon in **Figure 6**. This video documentation was invaluable, as it allowed us to observe the AGV's actions in real-time and to later analyze its path frame by frame. Observing the AGV's movement on video also helped in identifying any subtle deviations that might have been missed during live testing, providing a comprehensive view of its navigation behavior.

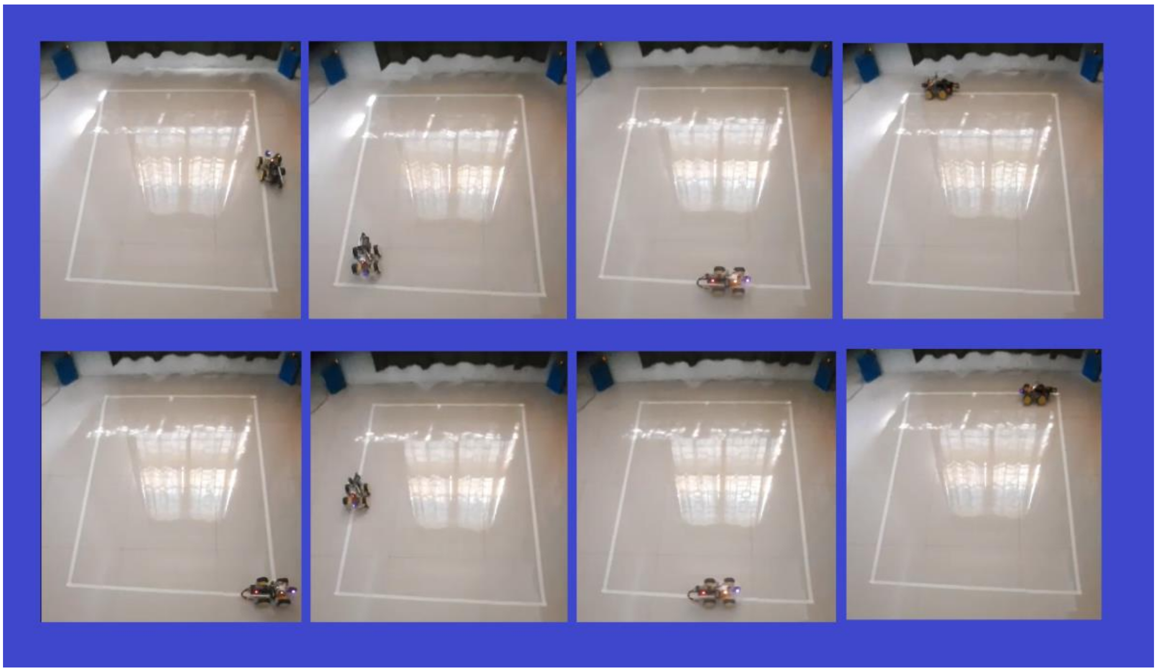

Figure 6. Recorded video footage of movements

During testing, in figure 7 observed a drift **of approximately 5 cm to the left and right** from the intended path. This level of drift was deemed acceptable, as it falls within the typical accuracy range of the Ultra-Wideband (UWB) system being used, which provides around **10 cm precision**. While this slight drift indicates minor positional variations, it is considered normal given the limitations of UWB technology. Accepting this drift as part of the system's operational tolerance allows us to proceed with confidence in the AGV's overall performance within its design constraints.

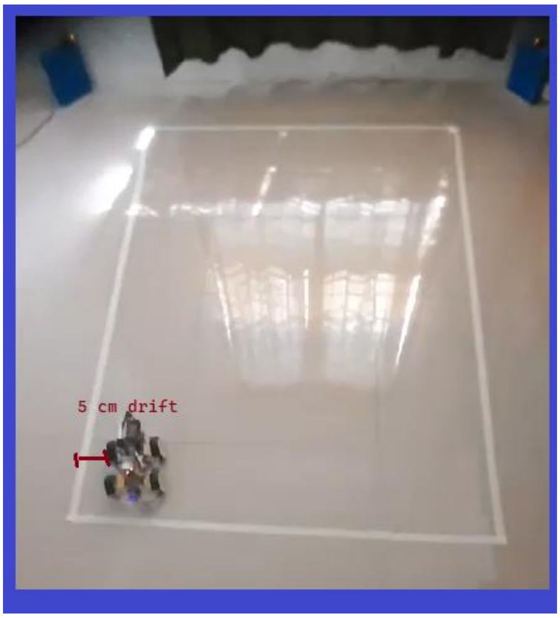

Figure 7. Observed approximately 5cm drift to the left

The testing and evaluation phase yielded valuable insights into the AGV's navigation performance and highlighted both strengths and areas for improvement. The marked floor provided a clear framework for assessing the AGV's adherence to its path, while the waypoint-based navigation allowed us to observe its ability to reach specific targets accurately. Video analysis confirmed that the AGV consistently followed the designated route with minor deviations. Notably, a drift of approximately 10 cm was observed in its movements—an acceptable margin within the expected accuracy range of the UWB system, which has a typical precision of around 10 cm. This level of drift was considered normal and did not impact the AGV's ability to perform its tasks reliably. Overall, the tests confirmed that the AGV's navigation system is stable and effective within its design parameters, with any observed drift falling within an acceptable range for its intended applications. These results underscore the AGV's readiness for operational use, while also providing a basis for future refinements to further enhance its accuracy and reliability.

D. Conclusion

In conclusion, this study has demonstrated the effectiveness of Ultra-Wideband (UWB) technology, specifically using the DWM1001 module, for achieving precise and reliable navigation in automated guided vehicles (AGVs) designed for indoor environments. The DWM1001 was selected over the DWM1000 due to its integrated microcontroller, ease of configuration, and better compatibility with the demands of indoor navigation. Testing revealed that the AGV achieved a consistent positional accuracy within a 10 cm margin, which is within the acceptable range for UWB technology. This level of accuracy was sufficient for the AGV to navigate effectively within confined spaces, confirming the robustness of the UWB-based localization approach in delivering dependable AGV performance. The integration of this module in AGV systems presents a promising solution for industries that require high-precision navigation in limited indoor areas.

For future work, it is recommended to explore additional refinements to further enhance the AGV's accuracy and operational efficiency. One potential area of improvement involves developing advanced algorithms to compensate for minor drift, thereby pushing the limits of UWB-based accuracy beyond the observed 10 cm margin. Additionally, implementing sensor fusion techniques that combine UWB with other positioning technologies, such as visual or inertial sensors, could offer enhanced stability and accuracy. Expanding the system's testing to include dynamic, multi-AGV environments would also provide insight into its scalability and real-time adaptability in more complex indoor settings. These enhancements would not only strengthen the reliability of AGV systems using UWB but also pave the way for their broader application in high-demand, precision-oriented fields.

E. Acknowledgment

This project is suppoorted by Pradita Universitya and The Directorate General of Higher Education - Indonesia.

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