HIGH-PRECISION LOCALIZATION FOR AGV-BASED ULTRA-WIDEBAND INDOOR POSITIONING SYSTEM

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***Abstract*—**Technological advancements have made indoor positioning systems (IPS) increasingly essential, prompting the adoption of innovative techniques and algorithms. IPS has seen widespread application in commercial and industrial settings, such as equipment tracking and object identification, due to its enhanced accuracy. However, its use in autonomous vehicles, particularly Automated Guided Vehicles (AGVs), remains limited. Positioning is critical for AGV operation, and although there are various methods available, such as IMUs, encoders, ultrasound, and LiDAR, these local positioning methods suffer from the inability to recover from positioning errors without human intervention. This paper presents an overview of an IPS solution for AGVs using Ultra-Wideband (UWB) technology.

Keywords: Indoor Positioning System, Ultra-Wideband, AGV, Localization

I. INTRODUCTION

Recent advancements in ubiquitous computing, where everyday devices are interconnected to collect data and deliver services, have paved the way for numerous applications that significantly enhance quality of life. Among these innovations, location-based services have become essential in navigation and positioning by integrating user location data with smart applications to deliver contextually relevant services.

Ultra-Wideband (UWB) technology has garnered considerable attention, particularly in radio frequency-based positioning systems that consist of fixed anchors (ANCHORs) and mobile tags (TAGs). These systems enable accurate indoor positioning in environments where GPS signals are ineffective or unavailable [1][2][3][4][5]. UWB systems track object movements using techniques such as distance estimation via wave reflection (RADAR principle), time of flight (ToF), time of arrival (ToA, TDoA), angle of arrival (AoA), and received signal strength indicator (RSSI) mapping. UWB technology offers distinct advantages over other systems, such as BLE and WiFi, owing to its large bandwidth (500 MHz), which allows for high time resolution and precise range measurements [6][7]. Research indicates that UWB can cover distances of up to 200 m with an accuracy of less than 50 cm, while maintaining low power consumption (30mW) [8][9].

Autonomous Guided Vehicles (AGVs) rely heavily on precise localization to function effectively. Traditional local positioning methods, such as those using inertial measurement units (IMUs), encoders, or LiDAR, are prone to cumulative errors over time, potentially leading to severe operational issues. In contrast, global localization techniques—such as those using GPS, radar, or external cameras—can correct positioning errors and maintain accuracy over extended periods. Combining both local and global localization techniques provides AGVs with enhanced accuracy, thereby reducing operational risks.

One promising global localization solution for AGVs is the use of Indoor Positioning Systems (IPS). Several IPS have been developed using WiFi, BLE, or ultrasonic technology [10][11][12][13]. However, these systems often face challenges in terms of operational range and accuracy [14]. For instance, BLE-based positioning systems typically achieve an accuracy of 1 to 2m within a 100m radius, as noted in [15]. Similarly, WiFi-based systems offer accuracy in the range of 6 to 8m, though this can be improved to 1 to 2m with the application of optimal algorithms. In comparison, UWB, with its superior range and accuracy, presents significant advantages for building advanced positioning systems over BLE and WiFi. In this paper, we implement UWB as a global localization method for AGVs, a technology that has already shown success in industrial environments [16].

This research explores the integration of UWB-based indoor positioning systems as a global localization solution for AGVs. UWB technology provides greater accuracy and range than BLE or WiFi-based systems, making it particularly suitable for industrial applications. Previous studies have investigated various indoor positioning systems, with BLE and WiFi being widely used due to their low cost and extensive availability. However, these technologies often show limited accuracy; BLE positioning typically achieves an

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accuracy of 1-5m, which can vary significantly in environments with high signal interference and multipath effects [10][11]. Similarly, WiFi-based systems provide moderate accuracy within 2-5m, which is also sensitive to environmental conditions and signal reflection [17]. In contrast, UWB has demonstrated high resilience to multipath interference and the ability to maintain accuracy in both open and confined environments, reaching localization accuracies within 2-50cm in optimal settings [18]. Recent research on UWB-based localization systems, such as the work by [19], has shown promising results in dynamic environments like manufacturing floors, where accurate AGV navigation is critical. These studies have mainly focused on static object tracking or simplistic mobility scenarios but often lack detailed examination in confined industrial spaces, where obstacles and layout complexity may affect system performance. This study contributes to the field by specifically investigating the effectiveness of UWB in confined environments, such as warehouses, highlighting its potential to enhance AGV localization with high precision and improved resilience to spatial constraints.

II. SYSTEM DESIGN

In this paper, we developed a UWB-based positioning system to provide a precise localization solution for AGVs. The system is designed to operate in a two-dimensional spatial environment, which is common for AGV applications such as warehouses, yards, or shopping mall floors. These spaces typically have flat, unobstructed surfaces with regular shapes, such as square, rectangular, or circular, making them ideal for wireless communication systems and optimizing the operational range of radio devices. The system's design is based on the mathematical principles of planar geometric coordinates. The core objective is to calculate the coordinates of a mobile object (TAG) using two known points (ANCHORs) on a plane. By combining the ability to measure distances between UWB devices, a highly accurate positioning system can be realized. To implement this system, two UWB devices, referred to as ANCHORs, are placed at fixed locations within the environment. The distances between the ANCHORs are measured, and coordinates are assigned to these fixed points (as shown in Figure 1). These ANCHORs then serve as reference points for determining the location of the TAG. The TAG is attached to the AGV, and the system calculates the current coordinates of the AGV by measuring the distances between the TAG and each ANCHOR. This completes the setup of the system model (Figure 2). Additionally, for real-time tracking, the TAG is connected to the internet, and its coordinates are continuously transmitted to a program for visualization. The coordinates of the TAG are calculated using a system of equations (Equation 1), where represent the coordinates of ANCHOR A and ANCHOR B, respectively, and a and b represent the distances from the TAG to ANCHOR A and ANCHOR B. The main components of this positioning system include UWB nodes, each comprising a UWB communication module and a microcontroller for data retrieval. In this study, we use the DW1000 UWB module (as shown in Figure 1), which provides a communication range of up to 200m and positioning accuracy of $\pm$10cm (Table I). To complete the UWB node, we selected the ESP32 microcontroller, which offers low power consumption, robust network protocol support, and the capability to communicate with the UWB module and transmit data via network protocols (Table II). The next step involves integrating the positioning system with the AGV. The AGV used in this study is a simple autonomous vehicle capable of operating based on predefined rotation angles and movement distances. For example, when given a command to rotate 45° to the right and move forward 3m, the AGV can execute the command with high precision, with rotational errors of less than 5° and distance errors of less than 5cm. This AGV is well-suited for testing the UWB-based positioning system.

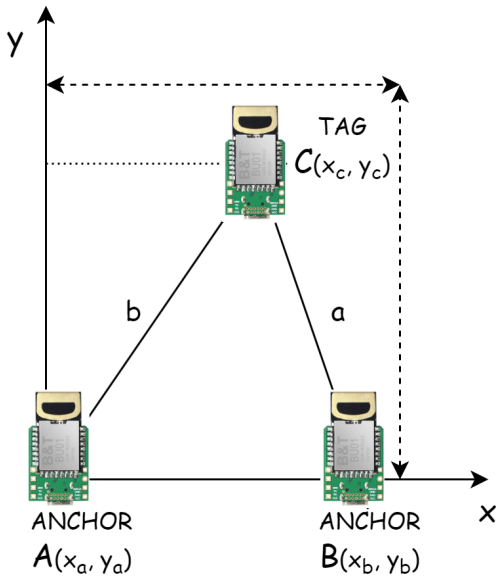


Fig. 1. UWB DW1000 device and positioning model

Coordinate equation system (1) according to the model in Figure 1:

$$\begin{cases} (x_C - x_A)^2 + (y_C - y_A)^2 = b^2 \\ (x_C - x_B)^2 + (y_C - y_B)^2 = a^2 \end{cases} \quad (1)$$

III. EXPERIMENT

After constructing the UWB positioning system, we conducted two stages of testing:

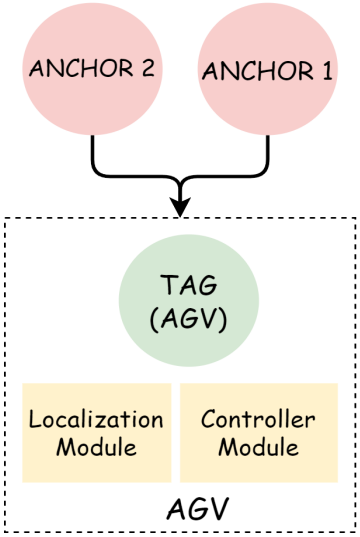


Fig. 2. System model

TABLE I
TECHNICAL SPECIFICATIONS OF THE UWB DW100 DEVICE

Name	Ultra-Wideband UWB DW1000 BU-01
Main IC	Decawave's DW1000 UWB
Power	2.8 - 3.6VDC, default 3.3VDC
Power sleep mode	$\leq$ 1mA
Frequency range	3.5 - 6.5 GHz
Interface	SPI
Accurary	10cm
Range	up to 200m
Data rate	110kbps, 850kbps, 6.8Mbps

- Testing the UWB positioning system.
- Testing the AGV integrated with the indoor positioning system.

a. Testing the UWB positioning system

In the first phase, the research team tested the UWB positioning system by mounting the UWB nodes on fixed supports, as shown in Figure 3-a. To evaluate the system's accuracy, the team compared the UWB measurements against a high-precision measurement device, the Xiaomi Atuman Duka LS-P, which has a maximum measurement range of 40m and an accuracy of ±2mm.

The test was conducted in a two-dimensional rectangular space measuring 3m in width and 7m in length, simulating a small room. Although this space does not fully leverage UWB's wide coverage capabilities, the focus of this study is on the system's accuracy. Additionally, the compact size of the AGV (15cm by 20cm) makes this test area appropriate for the experiment.

TABLE II
TECHNICAL SPECIFICATIONS OF ESP32 MICRO-CONTROLLER

Power	2.8 - 3.6VDC, default 3.3VDC
Power mode	Active, Modem-sleep, Light-sleep, Deep-sleep
Interface	SPI, UART, I^2C
Wireless	WiFi, BLE
SRAM	520KB
Security	Secure boot, AES, RSA, ECC...

The test preparation followed a structured process. First, the ANCHORs were strategically placed at opposite corners of the test area to optimize radio coverage. The distance between the two ANCHORs was measured using a high-precision device, and their coordinates were assigned based on these measurements. Similarly, the distance between the TAG and the ANCHORs was measured, and the coordinates of the TAG were calculated using Equation 1. This setup provided a reliable reference for the UWB-based positioning system.

During the experiment, the research team first evaluated the accuracy of the distance measurements between the TAG and the ANCHOR using UWB technology. The measurements were taken at fixed distances of 1m, 2m, 3m, and 4m. For each distance, the TAG was moved to various points at the same distance from the ANCHORs, and 200 samples were collected for each position. The accuracy of these measurements will be analyzed in detail in Section IV.

Next, the research team evaluated the UWB system's ability to determine the TAG's coordinates within the test space. The TAG was placed at arbitrary points, and the resulting position was recorded and displayed in Figure 4.

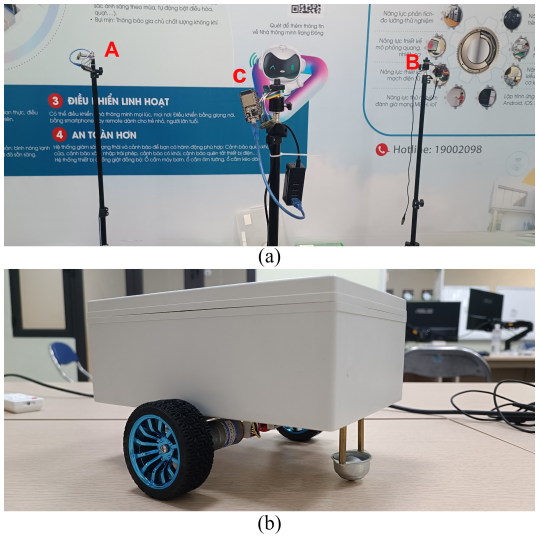
b. Testing the AGV Integrated with the UWB Positioning System (Revised) After evaluating the UWB positioning system, the next phase involved testing the AGV integrated with the UWB-based positioning system. The AGV model was prepared with basic modules, as depicted in the block diagram in Figure 2. The actual image of the AGV is shown in Figure 3. When integrating the TAG with the AGV, the positioning error includes both the UWB error and the AGV's speed measurement error.

To assess the accuracy of the combined system, the AGV was programmed to move horizontally and vertically within the test space. For horizontal movement, the AGV was instructed to travel through five coordinate points, starting from the edge of ANCHOR 1 to ANCHOR 2, with each point spaced 50cm apart (Figure 6). For vertical movement, the AGV started from a point between two ANCHORs and passed through five positions, each spaced 100cm apart (Figure 7). The accuracy of the positioning results will be discussed in Section IV.

IV. RESULTS AND DISCUSSION

a. UWB Positioning System Test Results

The results of the distance measurements between the TAG and ANCHOR are shown in Figure 5. In



(a)

(b)

Fig. 3. Experimental arrangement

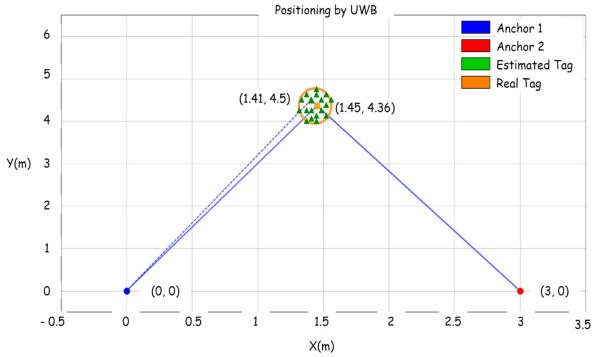


Fig. 4. Positioning results

this figure, the x-axis represents the sample number, while the y-axis shows the distance between the TAG and the ANCHOR. The error rate was found to be the largest at a distance of 1m, and it decreased as the distance increased. Overall, the distance measurement accuracy was relatively high, with an error rate of 5cm - 12cm for distances up to 1m. However, the error rate decreased as the distance between the TAG and ANCHOR increased. Nevertheless, there is a saturation range, beyond which the UWB measurements become less accurate as the distance between the TAG and ANCHOR increases. This also indicates that when the TAG is closer to the ANCHOR, the coordinate error tends to be larger.

Next, the results of determining the TAG's position at arbitrary points in the test space are presented in Figure 4. The figure shows the following:

The blue and red points represent the ANCHORs. The orange points represent the actual coordinates of the TAG, measured by a high-precision device. The green points represent the coordinates calculated by the UWB system. The orange circle represents the error range, indicating that the coordinate error from the UWB system does not exceed this circle. The error circle was drawn based on the collection of multiple sample results at the same position. As seen in Figure 4, the UWB positioning system provides coordinate measurements with errors within $\pm 5\%$ of the actual position. The blue points within the yellow circle in Figure 4 illustrate this.

b. Results of Testing the AGV Integrated with the UWB Positioning System

The results of the AGV integration tests are shown in Figures 6 and 7. The blue points indicate the AGV's actual position, determined by high-precision measuring devices, while the red D points represent the coordinates provided by the UWB positioning system. These coordinates reflect the combined errors from both the UWB system and the AGV's movement. Each test point was measured 10 times, and the averaged coordinates were used to determine the positioning accuracy at each location. This repetition helped reduce random noise and enhance the reliability of the data by mitigating small fluctuations in the UWB signal. In Figure 6, the horizontal movement test was conducted, where the AGV traveled through positions spaced 50cm apart. The positioning error ranged from 10cm to 18cm, with the error increasing as the AGV approached the ANCHORs. This test setup, with the TAG moving horizontally, allows for an assessment of maximum errors when the TAG is in closer proximity to the anchors, highlighting potential multipath effects and signal interference, which are known to intensify near UWB anchors. This horizontal movement provides insight into the system's error behavior along the x-axis. Figure 7 shows the results of the vertical movement test, where the AGV moved along a path closer to the anchors, allowing for an evaluation of the positioning error along the y-axis as the AGV moved vertically. The positioning error decreased from 15cm to 10cm as the AGV moved further away from the ANCHORs. The vertical test, with the TAG positioned nearer to the anchors, is designed to capture the highest potential errors when the TAG is in closest proximity to the anchors, providing critical data on error behavior under such conditions. This vertical movement simulates AGV movement along the y-axis in confined spaces. Together, these two tests in Figures 6 and 7 represent both horizontal and vertical movement patterns of the AGV. They provide a comprehensive assessment of the system's positioning error in both directions and help identify error patterns when the TAG is nearest to the anchors. In both tests, the AGV's movement error was limited to less than 3cm, meaning that the primary source of error can be attributed to the UWB system.

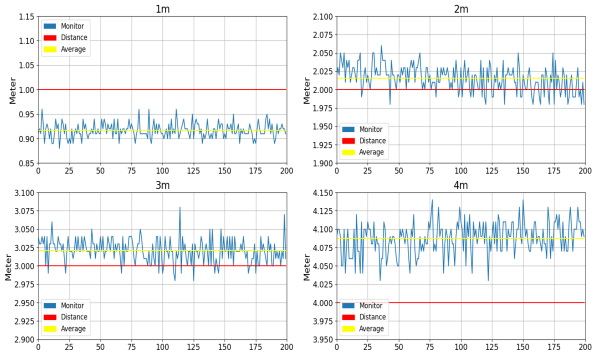


Fig. 5. Results of measuring fixed distances

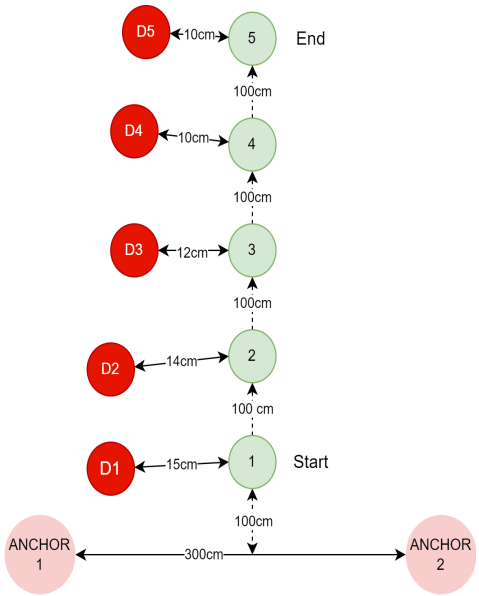


Fig. 6. System testing with AGV

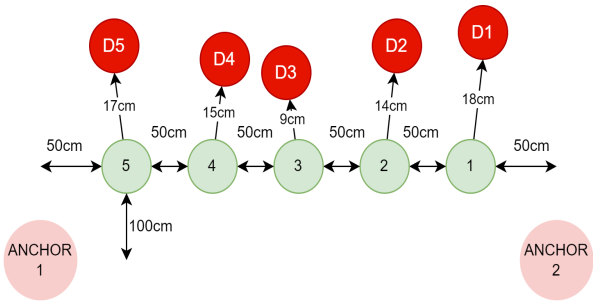


Fig. 7. System testing with AGV

V. CONCLUSION

This study successfully developed a high-precision indoor positioning system based on UWB technology. The experimental results from integrating the UWB positioning system with the AGV demonstrated that the overall positioning error, which included both UWB system error and AGV movement error, remained within an acceptable range. Specifically, in the 3m by 7m test space, the total positioning error was maintained within 20cm, making this system suitable for indoor environments such as warehouses and factories where GPS is unavailable. It is important to note that the system's accuracy may depend on the testing environment. However, due to certain limitations, this study did not conduct a full survey across different environmental conditions. While the test area did not fully utilize UWB's maximum range, the achieved accuracy was sufficient for AGV applications. The number of measurements at each test point was adequate, as the variation between individual measurements was minimal. This consistency supports the reliability of the system's accuracy within the tested setup. The arrangement and number of UWB devices play a crucial role in positioning accuracy. A well-planned placement of UWB anchors ensures optimal signal coverage and minimizes multipath interference, thereby enhancing the AGV's positioning capabilities and operational efficiency. Increasing the number of anchors would further improve the system's accuracy, especially in larger or more complex environments. Future work could explore optimized anchor configurations and conduct tests in diverse indoor settings to assess the robustness of the system across different conditions, further broadening its applicability in industrial AGV navigation.

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ĐỊNH VỊ CHÍNH XÁC CAO CHO AGV DỰA TRÊN HỆ THỐNG ĐỊNH VỊ TRONG NHÀ SỬ DỤNG BĂNG THÔNG SIÊU RỘNG

Tóm tắt - Các tiến bộ công nghệ đã khiến hệ thống định vị trong nhà (IPS) ngày càng trở nên thiết yếu, thúc đẩy việc áp dụng các kỹ thuật và thuật toán đổi mới. IPS đã được ứng dụng rộng rãi trong các môi trường thương mại và công nghiệp, như theo dõi thiết bị và nhận dạng đối tượng, nhờ vào độ chính xác được cải thiện. Tuy nhiên, việc sử dụng IPS trong các phương tiện tự hành, đặc biệt là các phương tiện dẫn đường tự động (AGV), vẫn còn hạn chế. Định vị đóng vai trò quan trọng trong hoạt động của AGV, và mặc dù có nhiều phương pháp khác nhau như IMU, bộ mã hóa, sóng siêu âm và LiDAR, các phương pháp định vị cục bộ này vẫn gặp khó khăn trong việc khắc phục sai số định vị mà không có sự can thiệp của con người. Bài báo này trình bày một giải pháp IPS cho AGV sử dụng công nghệ băng thông siêu rộng (UWB).

Từ khóa - Hệ thống định vị trong nhà, băng thông siêu rộng, AGV, định vị.



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