Implementation of High-speed Indoor Positioning System based on IEEE802.15.4z UWB

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Abstract

A high-speed indoor positioning system using IEEE 802.15.4z UWB technology was implemented. For UWB indoor positioning, location information of three or more fixed UWB devices and distance information to the corresponding devices are required. However, when using the conventional TWR-based UWB method, it takes a lot of time to obtain distance information. In this paper, the distance from three fixed UWB anchors to a moving tag are measured by the Combined TWR method, and then the measured distance from each anchor and anchor location information are sequentially transmitted to the tag through UWB communication. Based on this information, the moving UWB tag determines its position through trilateration. As a result of indoor positioning experiments with the implemented system, it was possible to implement a high-speed indoor positioning system capable of estimating the position of one tag at a high speed of 121 times per second. These results are expected to help apply UWB technology in various industries that require fast and accurate indoor positioning.

Keywords

UWB, Real-time Positioning, Two-Way Ranging, Anchor, Tag

1. Introduction

Indoor Positioning System (IPS) is a system that allows objects or people to determine their location and estimate their movement path in an indoor environment, where GPS satellites cannot reach. It is widely used for indoor navigation, autonomous navigation of robots, etc. The general concept of indoor positioning technology is illustrated in Figure 1. In an indoor environments, wireless devices such as smartphones or robots can calculate their position using trilateration based on the positions of three fixed wireless devices ((x_1, y_1), (x_2, y_2), (x_3, y_3)) and the distance to each device (d_1, d_2, d_3) [1,2].

Various technologies for indoor positioning systems are currently being proposed, including image-based, radar-based, and wireless communication-based technologies. Wireless technology, in particular, has gained attention due to its ability to perform indoor positioning without being affected by factors such as lighting. Examples of wireless technologies used in these devices include Wi-Fi, Bluetooth Low Energy (BLE), RFID, and Ultra-Wide Band (UWB). UWB technology, in particular, is currently attracting attention due to its advantage of providing high precision positioning at the centimeter level compared to Wi-Fi and BLE, which have a resolution in meters [3,4]. To construct an indoor positioning system using wireless technology, wireless devices called anchors or beacons are required. These devices are installed at fixed locations and provide their location information.

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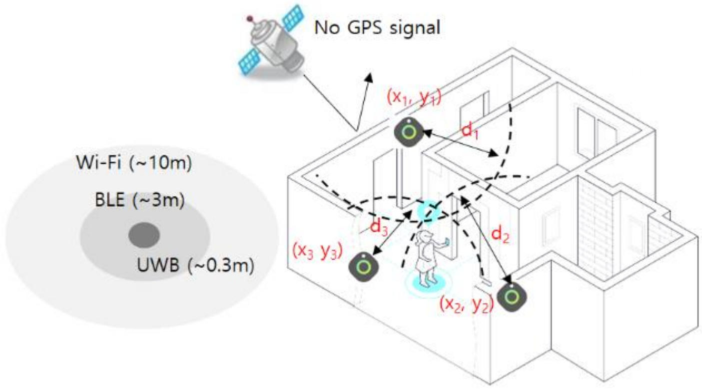


Figure 1: Concept diagram of indoor positioning technology.

It is worth noting that the positioning speed suggested in previous studies may vary depending on the specific use case. Fast-moving people or autonomous navigation of mobile robots present challenges for indoor positioning systems. These challenges arise due to the need to perform position calculations while the objects are in motion, and the potential for position changes between measurements. It is essential to address these challenges and discuss potential solutions.

In UWB standards, the Two-Way Ranging (TWR) method is commonly employed for distance measurement. Usually, the Double Sided TWR (DS-TWR) technique is frequently utilized, which involves three messages (Poll-Response-Final). However, since the UWB standard only describes the DS-TWR distance measurement method between a pair of UWB devices, it is necessary to implement DS-TWR with three or more fixed UWB devices to provide a practical positioning service [5,6].

Performing DS-TWR individually for each fixed UWB device can be time-consuming during the positioning process. Additionally, when the device is in motion during indoor positioning, accuracy may decrease as the position may change between measuring the distance to one anchor and the next. Previous studies have suggested position calculation frequencies of 40 times per second (40Hz) [7] and 33 times per second (33Hz) [8] for UWB devices. However, such position calculation speeds are difficult to apply to positioning for fast-moving people or autonomous navigation of mobile robots. In order to improve the UWB positioning speed, research using other position calculation methods, such as Time Difference of Arrival (TDoA) in addition to TWR are being conducted. However, these approaches have the drawback of requiring synchronization between anchors. Therefore, it is essential to increase the speed of indoor positioning while using the UWB TWR method as it is [9,10].

In this study, we implemented a fast and IEEE 802.15.4z UWB standard-compliant indoor positioning method by adapting the combined TWR method, which was initially designed to enhance the speed of UWB-based Real-Time Location Systems (RTLS) [11]. The positioning method implemented in this study is based on TWR and has the advantage of not synchronization between anchors while enabling fast positioning.

The structure of this paper is organized as follows. In Section II, we explain the operating principle of the UWB positioning method implemented in this paper and the differences between the positioning method used in this paper and the conventional TWR method in detail. Section III presents experimental results of the indoor positioning system implemented in this study. Finally, Section IV concludes this paper.

2. UWB Positioning Principle

2.1. UWB TWR Distance Measurement

The TWR distance measurement method used in UWB standards offers a significant advantage in that it does not require precise time synchronization between UWB devices. Each UWB device can

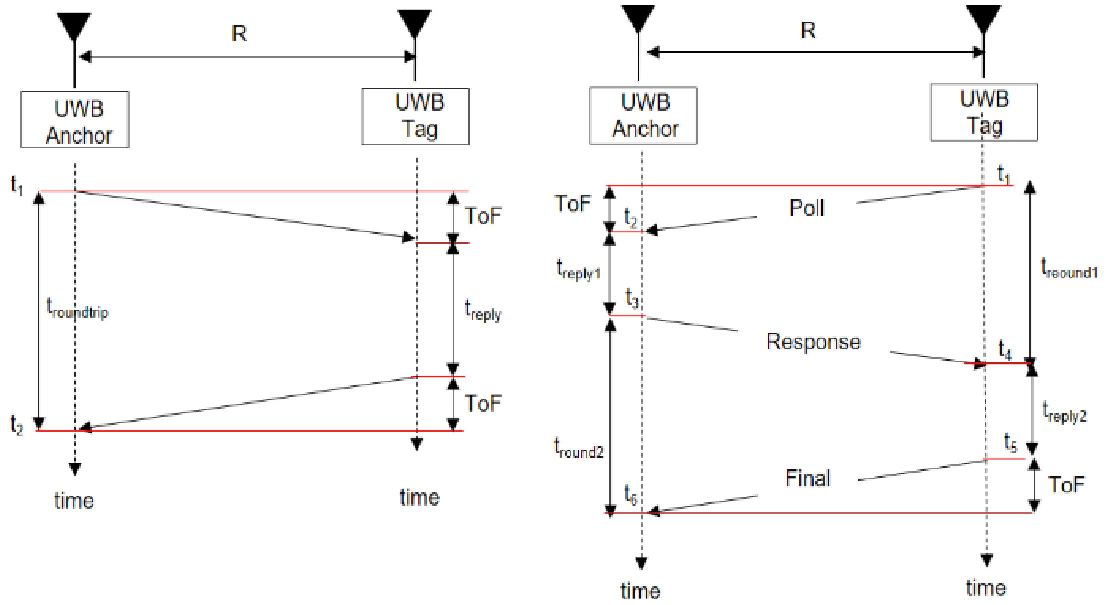


Figure 2: Comparison between SS-TWR (left) and DS-TWR (right).

utilize its own clock-based independent timestamp, enabling accurate distance measurement between UWB devices without the need for an external synchronization process.

TWR is divided into Single-Sided Two-Way Ranging (SS-TWR) and DS-TWR, as shown in Figure 2. SS-TWR is a method in which an UWB tag sends a pulse to an UWB anchor, and the anchor receives the pulse and sends it back to the tag to measure the Time of Flight (ToF). UWB anchor calculates the distance between the tag and the anchor based on this information. The specific operation method is as follows. The UWB Anchor transmits a message to the UWB Tag and records the transmission start time t_1. The UWB Tag device receiving the message sends a response message after a promised time t_2.

Now, the UWB Anchor records the timestamp t_3 when it receives this message. The distance between two UWB devices is now given by the time of arrival of the propagation (ToF) as

$$R = c \times \frac{t_2 - t_1 - t_{reply}}{2}, \quad (1)$$

Here, c represents the speed of light. However, it is important to clarify the scalability differences between SS-TWR and DS-TWR. In practical implementations, the DS-TWR method is predominantly used for indoor positioning systems due to its scalability advantages. DS-TWR involves multiple rounds of communication between the UWB tag and anchor, allowing for more accurate distance estimation. On the other hand, SS-TWR, although conceptually simpler, may face challenges when scaling to multiple tags or anchors, such as potential interference and synchronization issues. Therefore, to ensure efficient and reliable indoor positioning with multiple tags or anchors, the DS-TWR method is preferred.

DS-TWR is shown on the right side of Figure 2. If an UWB anchor wants to measure the distance, the distance measurement process starts by the tag transmitting a 'Poll' message. The tag records the timestamp $t_1$when sending the Poll message to the anchor. The anchor receives the Poll message and records the timestamp t_2, then sends a Response message after time t_{reply1}. Now, the UWB tag receives the Response message and records the timestamp t_4, completing one round. Subsequently, the UWB anchor receives the Final message from the UWB Tag, completing the second round.

In this DS-TWR process, if the same packet is used in the two rounds and the time is the same, it is called Symmetric Double-Sided Two-Way Ranging (SDS-TWR). If the time for the two rounds is different, it is called Asymmetric Double-Sided Two-Way Ranging (ADS-TWR). Generally, UWB uses ADS-TWR for distance measurement, and the distance is given by

$$R = c \times \frac{t_{round1} \times t_{round2} - t_{reply1} \times t_{reply2}}{t_{round1} + t_{round2} + t_{reply1} + t_{reply2}}, \quad (2)$$

When implementing (2), assuming ADS-TWR is used, the time from t_1 to t_6 takes only about 2 milliseconds. However, if there are multiple anchors, collisions may occur, and it takes a significant amount of time to exchange information with three or more anchors. Therefore, it is very challenging to perform indoor positioning at high speeds using ADS-TWR alone [11-13].

2.2. Proposed Combined TWR Positioning Technique

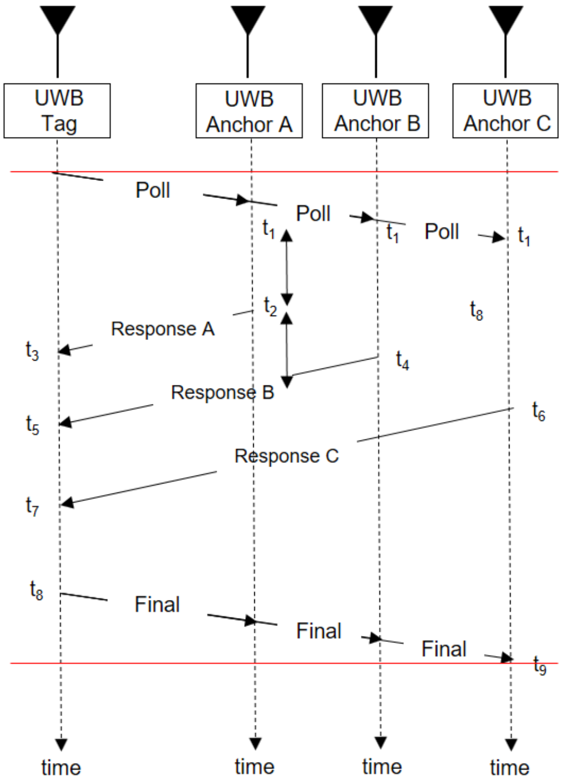


Figure 3: Location tracking procedure of UWB tag based on Combined TWR.

The Combined TWR technology is designed for quickly determining the position of a UWB tag when there are three or more UWB anchors [13]. In this method, a single Poll message from a UWB tag prompts three or more anchors to respond sequentially with time intervals. After successfully receiving the three responses, the tag sends a Final message to the anchors, completing the DS-TWR process. The Poll message employs the concept of Broadcast Poll, allowing all anchors to respond sequentially, reducing system complexity in a multi-device environment, and enabling the implementation of a fast and accurate indoor Real-Time Location System (RTLS), as shown in Figure 3. Typically, the distance information between each anchor and the measured tag is updated on a server connected to the anchor, allowing the server to track the tag's position in real-time. This method is designed for the implementation of indoor RTLS to track multiple tags in real-time and may be

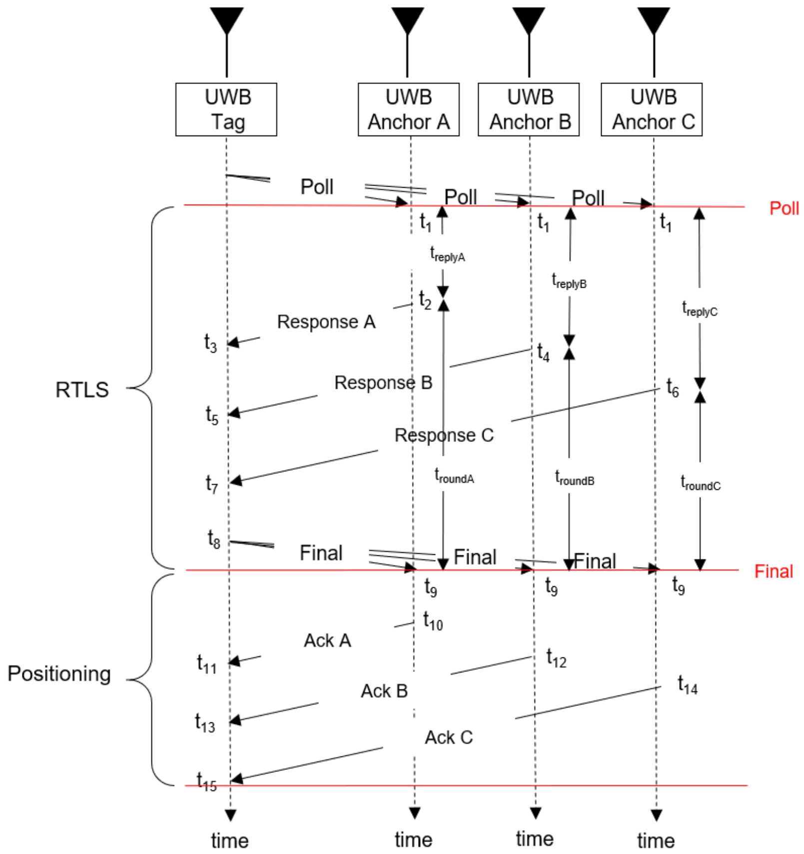


Figure 4: Suggested Combined TWR positioning procedure.

challenging to apply directly to indoor positioning technology for moving UWB tags to determine their own locations. The reason for this is that the tag transmitting the Poll message cannot determine its own position. In this paper, we have modified the Combined TWR method for positioning, as shown in Figure 4, to allow the tag to calculate its position information. The key to the modified method is that each anchor, after receiving the tag's Final message, sequentially sends an ACK message to the UWB tag requesting positioning, with the same time intervals. The ACK message includes the position coordinates of each anchor and the distance information measured by the anchor. Using this information, the tag can calculate its current position using triangulation.

Figure 4 visually represents the Combined-TWR positioning process implemented in this study, with $t_1 \sim t_9$ representing the time taken from Poll to Final in RTLS, and $t_9 \sim t_{15}$ representing the time taken for the tag to receive distance information from the anchors via ACK messages to calculate its position. In this study, the time values shown in Table 1 were used. The time taken up to RTLS is given by

$$t_{14} - t_9 + ToF = 2750us + 50.101ns = 2750.05us, \qquad (4)$$

Now, the time for the tag to sequentially receive ACKs is given by Table 1.

Thus, the total time consumption is the sum of (3) and (4), which theoretically takes a minimum of 5600µs, resulting in a frequency of 178.7Hz per second. However, this value assumes an ideal situation without any delay caused by the actual transmitter and receiver circuits.

Table 1
Combined-TDoA TWR positioning parameter.

Period	Name	Time (usec)
$t_1 \sim t_2$	t_{replyA}	1200
$t_1 \sim t_4$	t_{replyB}	1800
$t_1 \sim t_6$	t_{replyC}	2700
$t_2 \sim t_9$	t_{roundA}	1550
$t_4 \sim t_9$	t_{roundB}	950
$t_6 \sim t_9$	t_{roundC}	50
$t_1 \sim t_9$	-	2750
$t_9 \sim t_{10}$	t_{ackA}	1200
$t_9 \sim t_{12}$	t_{ackB}	1800
$t_9 \sim t_{14}$	t_{ackC}	2700
$t_9 \sim t_{15}$	-	2750+ToF

2.3. Trilateration -based Positioning

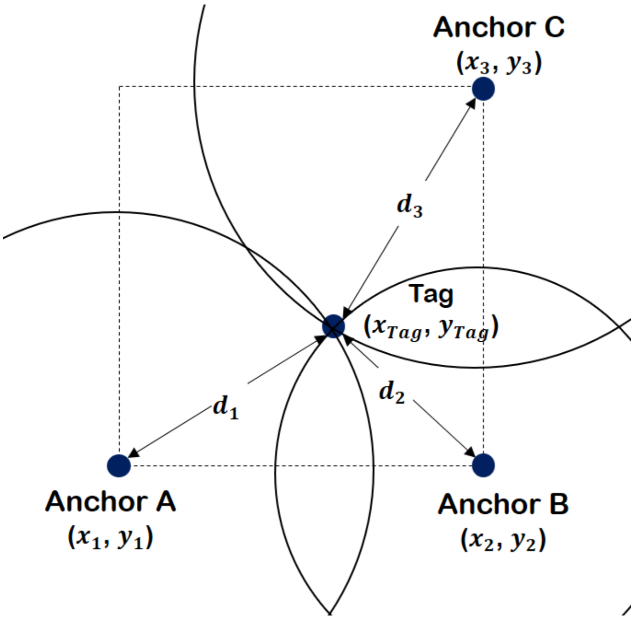


Figure 5: Triangulation.

Using the method shown in Figure 5, a UWB tag that has received the location information and distance of each anchor performs position estimation through trilateration. Trilateration is an algorithm that can be used for positioning in both 2D and 3D environments.

In this study, trilateration was employed to determine the position coordinates of the UWB tag in a 3D space. To accomplish this, the height of each anchor was measured and standardized, and the Pythagorean theorem was utilized to convert the 3D space into a 2D plane. By incorporating the measured distances between the three anchors and the tag, the tag's position coordinates were accurately determined using equations (5) through (12). Figure 5 provides a visual representation of the trilateration process, where the intersection of the circles drawn based on the distances from the three anchors corresponds to the coordinates of the tag. This approach enables precise positioning in a 3D environment, considering the distances measured in all three spatial dimensions.

$$A = -2 \times x_1 + 2 \times x_2 \quad (5)$$

$$B = -2 \times y_1 + 2 \times y_2 \quad (6)$$

$$C = {D_1}^2 - {D_2}^2 - {x_1}^2 + {x_2}^2 - {y_1}^2 + {y_2}^2 \quad (7)$$

$$D = -2 \times x_2 + 2 \times x_3 \quad (8)$$

$$E = -2 \times y_2 + 2 \times y_3 \quad (9)$$

$$F = {D_2}^2 - {D_3}^2 - {x_2}^2 + {x_3}^2 - {y_2}^2 + {y_3}^2 \quad (10)$$

$$x_{Tag} = \frac{(C\times E)-(F\times B)}{(E\times A)-(B\times D)} \quad (11)$$

$$y_{Tag} = \frac{(C\times D)-(A\times F)}{(B\times D)-(A\times E)} \quad (12)$$

3. Experiment and Results

3.1. Implementation of UWB Positioning System

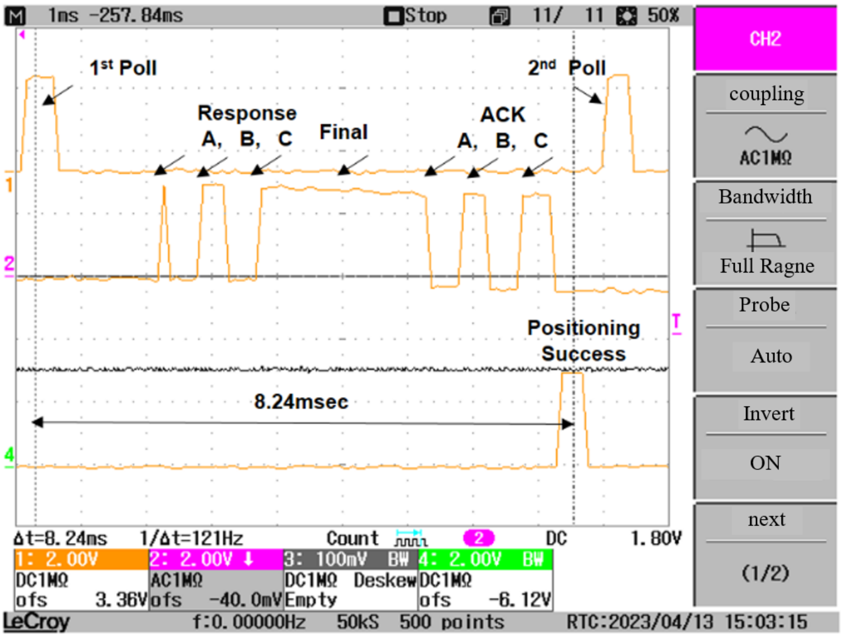
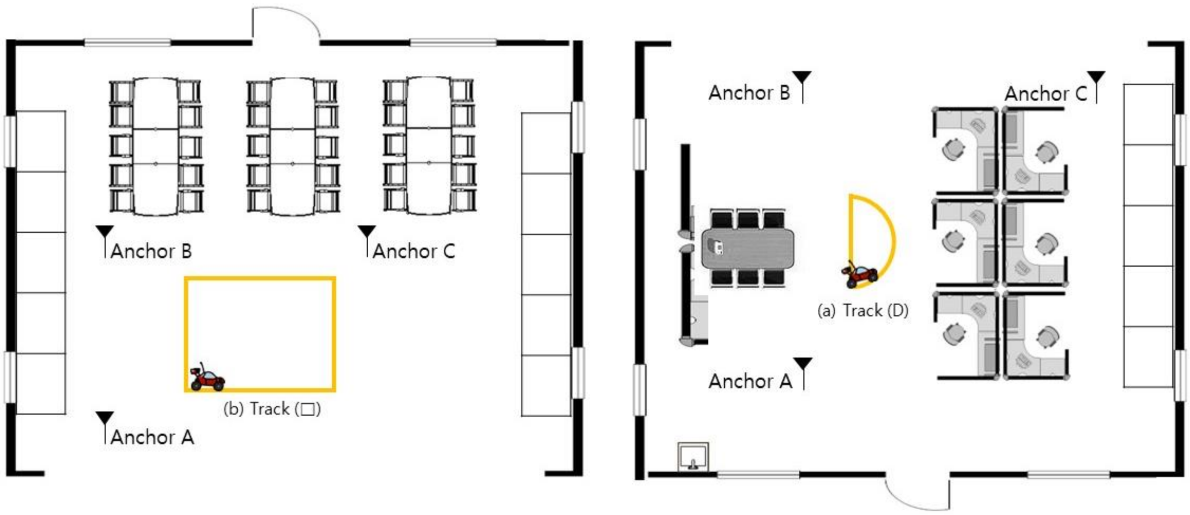


Figure 6: Packet time diagram at UWB tag.

The UWB device used in this study was implemented using Qorvo's DWS3000 module, which complies with the latest UWB standard, IEEE 802.15.4z-2020. The DWS3000 module is driven by a Nordic nRF-52840 microcontroller, and an embedded programs for each anchor were developed using the Segger Embedded Studio program, following the parameters specified in Table 1. During the programming, various UWB-related parameters such as frequency channels and packet transmission speed were adjustable. The DWS3000 module supports two carrier frequencies, CH5 (center frequency 6.4896 GHz) and CH9 (center frequency 7.9872 GHz). We used channel 9 which is available internationally. In addition, to confirm that the implemented system operates as shown in Table 1, the tag embedded program is added so that a pulse are output through an interrupt when a Poll message is transmitted or when a Response or ACK message is received, By measuring the occurrence time of these pulses using an oscilloscope, to measure measuring the time of these pulses with an oscilloscope, we were able to verify the tag's combined TWR operation.

Figure 6 shows the verification result of the operation of the proposed combined TWR method. In the case of 1:3 communication between three UWB anchors and one UWB tag, the time required for positioning once is estimated approximately 5.6 ms according to (3) and (4). However, it was measured that an additional delay time of 1.8ms was required due to actual hardware delay (e.g., antenna delay) even when the parameters of Table 1. In addition, in actual implementation, an additional delay time of 0.84ms was added due to due to various factors, resulting in a total of 8.24ms. Accordingly, it was experimentally confirmed that an actual positioning time of 121 Hz was required. In Figure 6, the time difference between Response C message and Final message was too short, so the pulse difference could not be distinguished by interrupt. However, it was confirmed that the proposed combined TWR worked as expected by confirming that the positioning data was received accurately.

3.2. Field Experiment Results



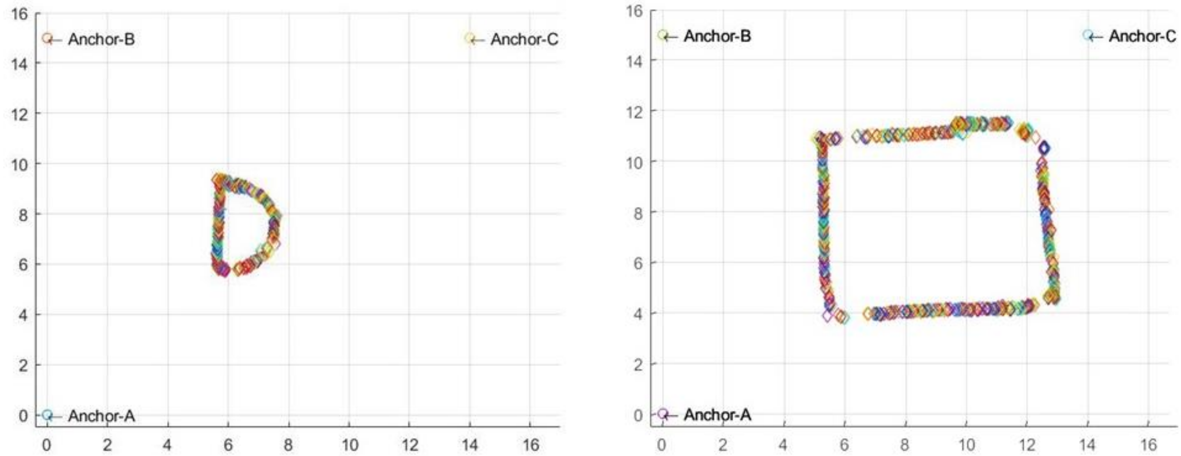
(a) Track shape (D) (b) Track shape (□)

Figure 7: Positioning experimental environment.

Two indoor field experiments were conducted to verify the high-speed positioning performance of the designed UWB positioning system. One experiment was conducted in an office setting, where the positioning system was tested for real-time positioning accuracy along a D-shaped track. The other experiment was conducted in a spacious studio environment, where the system's performance was evaluated for real-time positioning along a rectangular track.

In both experiments, conducted in different indoor environments, the UWB tag's nRF-52840 microcontroller established communication with a PC using UART communication. The real-time position information of the UWB tag was processed using MATLAB for further analysis and evaluation. To create the experimental setups, UWB Anchor modules were strategically placed at fixed coordinates using tripods. Specifically, the UWB Anchor modules were installed at the following locations: (0, 0), (0, 15), and (14, 15). These fixed coordinates served as reference points for the positioning system. The UWB tag was securely mounted on a remote-controlled model car (RC Car) that meticulously followed a pre-determined track designed for each experiment scenario. By adhering to the track, the model car ensured consistent and controlled movement, enabling the system to accurately determine and track its real-time position. The experimental setup is shown in Figure 7.

The results of the experiments are shown in Figure 8, where each position calculation is represented by a marker on the screen. Through these experiments, it was confirmed that the UWB tag's actual position could be accurately calculated in real-time, enabling it to determine its own location along the



(a) Track shape (D) (b) Track shape (□)

Figure 8: UWB positioning data in LoS environment.

designated tracks. The proposed combined TWR positioning system demonstrated stable operation, allowing the tag to determine its position accurately and quickly in real-time at a high speed of 121 times per second.

4. Conclusion

In this paper, a combined TWR-based UWB indoor positioning system was implemented using the IEEE 802.154z UWB standard. As a result of the experiment, it was confirmed that the accurate and stable positioning system is possible at a high speed of 121 times per second in an open indoor environment. The implemented high-speed UWB positioning system can be directly applied to various industrial fields where UWB positioning is required. Therefore, this study is meaningful in presenting the possibility of UWB technology being applied to positioning system development in various industrial fields. Especially, the development of UWB positioning technology is expected to be very useful in industrial fields where real-time tracking of fast-moving robots or moving objects such as forklifts is required. Moreover, the combined TWR-based UWB indoor positioning system proposed in this study is expected to have a significant impact on future research and technological developments and will lead to the advancement of UWB positioning technology.

5. Acknowledgements

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