

Deployment and Optimization of an UWB based Indoor Positioning System for Smart Factory

Wei-ming Chen, Tesfaye Wakessa Gussu, Yan-Ru Lai, and Che-Chien Chen

Abstract—With the rapid development of automation and smart factories, the use of indoor positioning devices is increasing. This emphasizes the importance of precise indoor positioning systems for increased safety and productivity. Various indoor localization technologies, including WIFI, Bluetooth, RFID, ZigBee, and UWB, have been developed to meet indoor positioning demands. Among these, UWB stands out as the technology with the highest positioning accuracy. However, their outputs are affected by multipath effects resulting from poor installation conditions, which have rarely been addressed. Thus, this study discusses various installation scenarios and a method for obtaining optimized positioning results. Then, the trilateration principle combined with the time-of-flight (TOF) is implemented to measure the tag position. Furthermore, a series of installation experiments was conducted with anchors and tags to optimize the results of the experimental setup. Finally, a generalized experimental configuration was selected with six positioning base stations within an area of 34.3 m x 24.5 m. The positioning accuracy was evaluated by measuring the positions at 21 different locations. The results demonstrated an average positioning accuracy of 22.6 cm. These findings highlight the potential of UWB technology to achieve high-precision indoor localization, making it a promising solution for applications in automation and smart factories.

Index Terms—UWB, Ultra-wideband, Indoor positioning, Anchor, Tag, Time-of-Flight, TOF.

I. INTRODUCTION

With the advancement of smart factories, the use of autonomous devices in indoor environments has increased, thereby creating a growing demand for collaboration between these devices and humans. Consequently, ensuring highest safety and increased productivity has become crucial. Thus, achieving high positional accuracy is one of the key indicators of both safety and high productivity. Various indoor position technologies have been developed and applied [1].

For instance, WIFI, as the most commonly used indoor transmission technology, offers advantages such as long transmission distance. It can be combined with RSSI (Received Signal Strength Indicator) [2], TOA (Time of Arrival) [3], AOA (Angle of Arrival) [4], and TDOA (Time Difference of Arrival) [5] techniques to calculate positioning accuracy based on

triangulation. The indoor positioning accuracy achieved was approximately less than 200 cm.

Bluetooth technology is also one of the primary communication technologies for mobile devices. When a handheld Bluetooth device enters a hotspot area, its position can be recorded and estimated [6, 7]. However, Bluetooth has a limitation on the number of hotspots in a fixed-sized space. If too many Bluetooth devices are present in the same area simultaneously, they significantly affects the positioning accuracy [8].

Radio Frequency Identification (RFID) that has been widely adopted in industrial automation, vehicle management, warehouse management, supply chain management, healthcare, and other fields due to its low cost and high accuracy [9, 10]. The RFID utilizes fixed antennas to convert radio signals into electromagnetic fields, allowing devices attached to objects to transmit information through induced currents. [11, 12] proposed RFID-based indoor positioning techniques utilizing TOA and TDOA methods.

ZigBee is a wireless transmission technology known for its low data rate and long transmission distance. It is commonly applied in home and industrial devices for tasks such as remote meter reading, lighting control, wireless smoke detection, and medical monitoring [13]. In conjunction with RSSI, ZigBee can be used for indoor localization of personnel and devices based on received signal strength. ZigBee can also expand the indoor positioning range by enabling communication between nodes. Compared to Bluetooth, ZigBee offers a low-complexity and cost-effective solution [14].

Ultra-Wideband (UWB) is a pulse-based radio frequency communication technology [15]. Its ability to utilize large bandwidth enables excellent ranging capabilities under specific conditions. UWB technology is commonly employed in communication and ranging applications. Compared to other indoor positioning technologies, UWB technology offers high penetrability and Anti-interference. When combined with Time-of-Flight (TOF) methods, UWB technology can obtain high positioning accuracy. However, it performs relatively poorer in terms of power consumption. Fig. 1 and Table I show common indoor positioning technologies and characteristics [1].

However, in practical applications of UWB-based indoor positioning systems, multipath interference and non-line-of-sight interference is unavoidable, leading to signal attenuation and ineffective of rendering some measurements. Consequently, this interference may result in offset in the obtained positioning coordinate's outputs. This indicates that less consideration is given to the contribution of proper anchor and tag installation

Wei-ming Chen is with Precision Machinery Research & Development Center, Taichung City, Taiwan. (e-mail: e11132@mail.pmc.org.tw).

Tesfaye Wakessa Gussu is with Precision Machinery Research & Development Center, Taichung City, Taiwan. (e-mail: e11023@mail.pmc.org.tw).

Yan-Ru Lai is with Precision Machinery Research & Development Center, Taichung City, Taiwan. (e-mail: e10606@mail.pmc.org.tw).

Che-Chien Chen, is with Precision Machinery Research & Development Center, Taichung City, Taiwan. (e-mail: e9811@mail.pmc.org.tw).

and its effect in achieving precise indoor positioning inside smart factories.

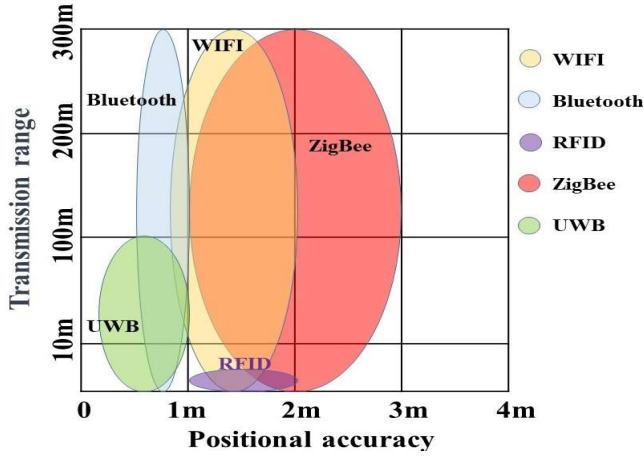


Fig. 1. Indoor position technologies

TABLE I
INDOOR POSITION CHARACTERISTICS

Item	WiFi	Bluetooth	RFID	ZigBee	UWB
Communication protocol	IEEE 802.11ax	IEEE 802.15.1	EPC/ISO	IEEE 802.15.4	IEEE 802.15.4a
Ranging technology	RSSI/TOA/AOA/TDOA	TOA/TOD	TOA/TDOA	RSSI	TOF/TDOA
Communication frequency	2.4GHz, 5GHz	2.4GHz	12.5kHz ~5.8GHz	868/915MHz, 2.4GHz	3.25~6.75 GHz
Transmission speed	300Mbps	24Mbps	106kbps	250kbps	480Mbps
Positional accuracy (meter)	<2m	<1m	<2m	<4m	<1m
Penetrability	Moderate	Moderate	Moderate	Strong	Strong
Anti-interference	Moderate	Weak	Weak	Weak	Strong
Power consumption	High	Low	Low	Low	High

In this paper, a method for finding optimal anchor placement, tag positioning error compensation approaches, and determining the maximum range of two different UWB system setups for an enhanced UWB-based positioning and localization is proposed. The result is then validated by numerical analysis for optimizing the measurement results. In the proposed technique, neither additional sensors nor a learning algorithms such as particle filters or deep learning are used. Furthermore, no prior knowledge of UWB tag positions, or accurate ground truth measurement equipment are required. Finally, the proposed method is tested in a complex factory environment addressing of all factors that cause multipath and NLOS effects.

The remainder of this paper is organized as follows. Section II discusses system setup for UWB-based indoor position system. While Section III discusses about optimal installation conditions, Section IV addresses the comparison of various installation methods. Finally, conclusions are addressed in Section V.

II. SYSTEM SETUP FOR UWB-BASED INDOOR POSITIONING SYSTEM

This research employs a UWB system with an experimental setup consisting of a server, WIFI, and anchors, as illustrated in Fig. 2. The positioning technique is based on trilateration, utilizing Time of Flight (TOF) measurements to determine the location of tags. TOF measures the flight time between a transmitter and a receiver to calculate the distance between two points, enabling precise positioning.

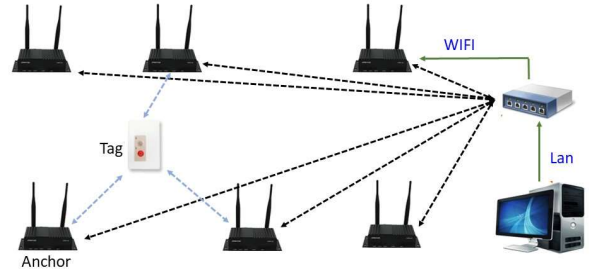


Fig. 2. UWB positioning system setup with anchors, WIFI-router, and server station for monitoring tag movement.

In this work, 21 positioning tags are measured with the help of 6 anchor as positioning bases. These positioning bases are then used to receive the packet data of the positioning tag which tag handles its own location positioning and message transmission. The UWB system uses Time of Flight (TOF) distance measurement technology and trilateration to locate the position of the object with tag attached to it, thereby establishing its precise location. The maximum distance between 3 positioning bases can reach 100 m, and the system has a better sensing range for measuring the space of 30m x 30m, within which 50 to 100 tag positioning tags can be placed.

Fig. 3 shows the trilateration principle adopted in [6]. The known coordinates of the three positioning anchors (A_1 , A_2 , and A_3) are used to calculate the distances between A_1T , A_2T , and A_3T using Equations (1) to (3).

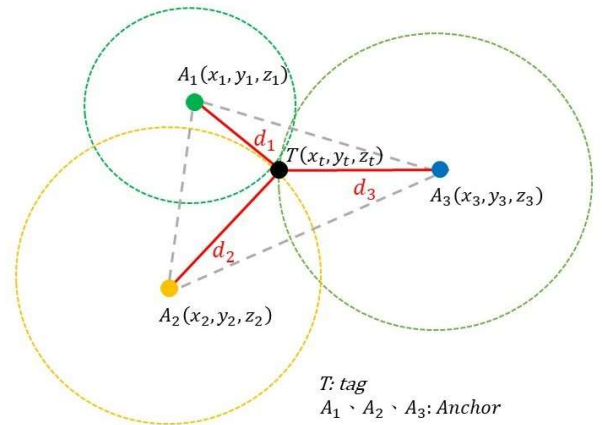


Fig. 3. Trilateration method for localizing and Tag position measurement

$$(x_t - x_1)^2 + (y_t - y_1)^2 + (z_t - z_1)^2 = d_1^2 \quad (1)$$

$$(x_t - x_2)^2 + (y_t - y_2)^2 + (z_t - z_2)^2 = d_2^2 \quad (2)$$

$$(x_t - x_3)^2 + (y_t - y_3)^2 + (z_t - z_3)^2 = d_3^2 \quad (3)$$

Expanding (1) to (3) yields:

$$x_t^2 - 2x_tx_1 + x_1^2 + y_t^2 - 2y_ty_1 + y_1^2 + z_t^2 - 2z_tz_1 + z_1^2 = d_1^2 \quad (4)$$

$$x_t^2 - 2x_tx_2 + x_2^2 + y_t^2 - 2y_ty_2 + y_2^2 + z_t^2 - 2z_tz_2 + z_2^2 = d_2^2 \quad (5)$$

$$x_t^2 - 2x_tx_3 + x_3^2 + y_t^2 - 2y_ty_3 + y_3^2 + z_t^2 - 2z_tz_3 + z_3^2 = d_3^2 \quad (6)$$

Equations (4) to (6) are further reorganized to give equation (7).

$$\begin{bmatrix} 2(x_1 - x_t) & 2(y_1 - y_t) & 2(z_1 - z_t) \\ 2(x_2 - x_t) & 2(y_2 - y_t) & 2(z_2 - z_t) \\ 2(x_3 - x_t) & 2(y_3 - y_t) & 2(z_3 - z_t) \end{bmatrix} \begin{bmatrix} x_t \\ y_t \\ z_t \end{bmatrix} = \begin{bmatrix} d_1^2 - x_1^2 - y_1^2 - z_1^2 \\ d_2^2 - x_2^2 - y_2^2 - z_2^2 \\ d_3^2 - x_3^2 - y_3^2 - z_3^2 \end{bmatrix} \quad (7)$$

Finally, the average value of the positioning error is obtained by measuring 30 sets of data using (7). Where A1, A2, and A3 are anchors, and T is the tag. d1, d2, and d3 represent the distances between anchor and tag.

III. OPTIMAL INSTALLATION CONDITIONS

Although the UWB system's positioning base consists a minimum of three anchors placed in a triangular arrangement, good positioning accuracy requires an optimal installation direction, or height of the base. Therefore, before conducting large-scale measurements, it was necessary to perform confirmation tests on the installation conditions.

Figs. 4 and 5 shows the experimental site with an area of 45.3 m x 31.7 m. The six positioning base stations were set up within an area of 34.3m x 24.5m. For this part of the experiment, it is mainly divided into two parts to find the optimal installation conditions for the positioning anchor and the sensing conditions for the positioning tag.



Fig. 4. Test field.

A. Installation conditions for anchors

In this part of the experiment, the positioning tags were fixed at a height of 100cm parallel to the floor and facing the direction of the equilateral triangle vertices. The three anchors closest to the positioning tags were placed equidistantly forming an equilateral triangle. Based on this setup, other conditions were varied for experimentation.

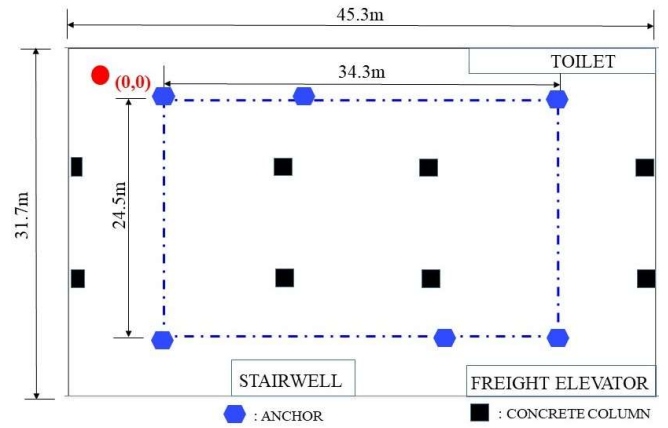


Fig. 5. Dimension of the testing area.

(a) Direction of Receiver on the Anchor: The placement of the receiver antenna on the anchor can impact its orientation, which is determined by its height and location. For example, if the anchor is affixed to the ceiling, the antenna will face downwards, causing it to be oriented in the opposite direction. If the factory's ceiling is excessively high, choosing to fix the anchor to the side wall instead might be a preferable option. In such a scenario, the antenna will be horizontally oriented, and the anchor coordinates can be found in Table II.

TABLE II
ANCHOR COORDINATES

Anchor Number	Actual Coordinates		
	X(cm)	Y(cm)	Z(cm)
016FBB	1260	380	280
016FF1	3440	406	280
016FF2	3431	2454	280
016FF3	60	2459	280
016FF4	60	380	280
016FF5	2460	2459	280

(b) Distance between anchors: The distance between the anchors in an equilateral triangle has an impact on the localization of the tag. However, it is still unclear whether the anchors should be placed closer to the tag for better performance. Therefore, three different anchor-to-anchor distances 24 m, 16 m, and 8 m were set to examine the effect of the anchors placement in the experiments, as shown in Fig. 6. Table III shows the coordinates of anchors.

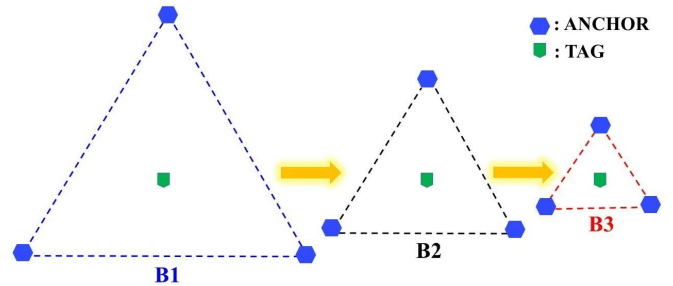


Fig. 6 Distance between two anchors

TABLE III

ANCHOR COORDINATES AT DIFFERENT DISTANCES

Anchor Number	Anchor Coordinates					
	Distance 2400 cm		Distance 1600 cm		Distance 800 cm	
	X(cm)	Y(cm)	X(cm)	Y(cm)	X(cm)	Y(cm)
016FBB	3431	2454	3431	2454	3431	2454
016FF1	60	380	60	380	60	380
016FF2	2460	2459	2060	2228	1660	1997
016FF3	3440	406	3440	406	3440	406
016FF4	60	2459	460	2228	860	1997
016FF5	1260	380	1260	842	1260	1304

Note: The placement height of all anchors is 280cm.

(c) Anchor height above ground: Due to the limited space in factories, which is affected by the placement of equipment, the height of the ceiling, and other factors, the positioning of anchors may need to be adjusted according to the needs. In this experiment, the height of the anchor placement was fixed at three different heights from the ground, which are 280 cm, 100 cm, and 25 cm (with the anchor placed on the floor), as shown in Fig. 7.

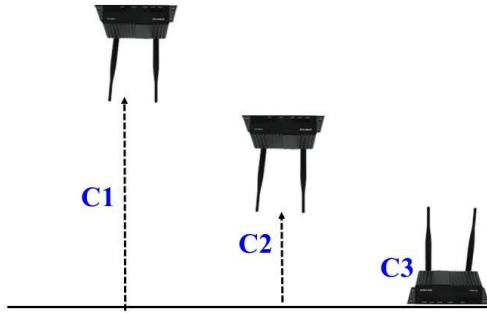


Fig. 7 Distance between anchor and ground.

(d) Comparison of the influence of factors: In this part of the experiment, the A, B, and C factors were used, each with 2 levels, 3 levels, and 3 levels respectively. A total of 18 sets of experiments were conducted under these three factors. Finally, by comparing the signal-to-noise ratio (S/N) using the smaller-the-better approach, we examined which level of each factor had a greater influence. The higher the S/N ratio, the better the influence on position accuracy. Fig. 8 illustrates the experimental results, indicating that the vertical placement A1 of the anchor has a greater impact compared to the horizontal placement A2. The reason for this is that under upright placement, the wireless signal can be transmitted further, resulting in better reception by the tag and thus a higher impact. It can also be seen from the results that the influence of the anchor is better when the anchor is placed at equal distances and closer to the tag, such as B3. This is because under closer conditions, it is less likely to be affected by other objects and other signals. As for the height at which the anchor is placed, it is found that placing the anchor higher than the tag has a better effect. From the figure, it can also be seen that the influence of the anchor placed at a height of 100cm (C2) is higher than that at a height of 280 cm (C1), but the difference is not significant. Table IV presents the experimental results.

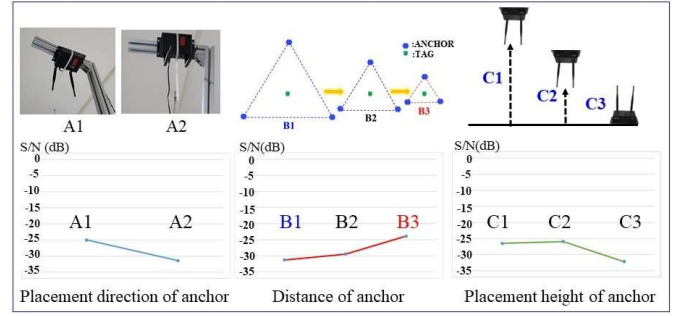


Fig. 8: Effectiveness of Anchors

TABLE IV
AVERAGE ERRORS OF ANCHORS

Number	A	B	C	Average error (cm)
	Anchor placement direction A1: Vertical A2: Horizontal	Anchor distance B1:2400 cm B2:1600 cm B3:800 cm	Anchor placement height C1:280 cm C2:100 cm C3:25 cm	
1	A1	B1	C1	3.7
2	A1	B1	C2	17.1
3	A1	B1	C3	34.8
4	A1	B2	C1	23.9
5	A1	B2	C2	17.9
6	A1	B2	C3	6.0
7	A1	B3	C1	7.7
8	A1	B3	C2	7.9
9	A1	B3	C3	11.7
10	A2	B1	C1	30.5
11	A2	B1	C2	25.0
12	A2	B1	C3	114.3
13	A2	B2	C1	28.5
14	A2	B2	C2	17.0
15	A2	B2	C3	45.7
16	A2	B3	C1	10.4
17	A2	B3	C2	4.8
18	A2	B3	C3	32.4

B. Tag Sensing Method

In this section, the anchors were fixed in an upright position (with the antenna facing downwards) at a height of 280 cm, and the three closest anchors to the tag were arranged in an equilateral triangle with a side length of 24 m. Subsequently, the placement method, height, and position of the tags were adjusted, and experiments were conducted.

(a) Orientation of tag placement: The tag placement at a height of 100cm can be divided into horizontal and vertical orientations. The reason for these two placement methods is that when the tag is fixed on an unmanned forklift or automated guided vehicle, it is usually placed horizontally or fixed on the table or roof of an unmanned forklift for convenience. However, when worn by personnel, the tag is usually hung around the neck and placed vertically on the chest.

(b) Tag height above ground: The distance between the tag and the ground was set at three different heights: 100 cm, 140 cm, and 180 cm. The purpose of this test was to investigate whether the positioning accuracy is affected when the tag is too close to the ground or the anchor. Fig.9 illustrates the different

tag heights used in the experiments.

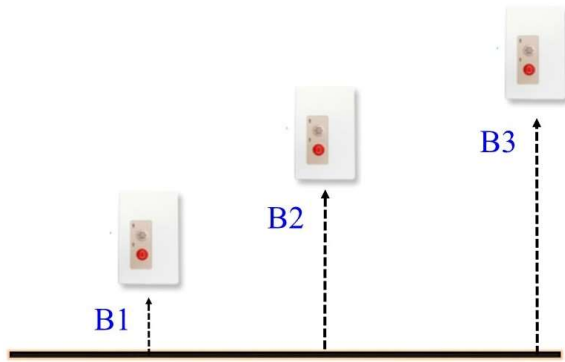


Fig. 9 The height of the tag above the ground.

(c) Tag position: This study placed anchors inside a triangle with a side length of 24 m. According to the manufacturer's recommendation, it is known that placing tags inside triangles with equal sides can result in higher positioning accuracy. However, it is still unclear whether any position inside the triangle can achieve high positioning accuracy. The tag is placed at a height of 100cm, and the placement positions are shown in Fig. 10.

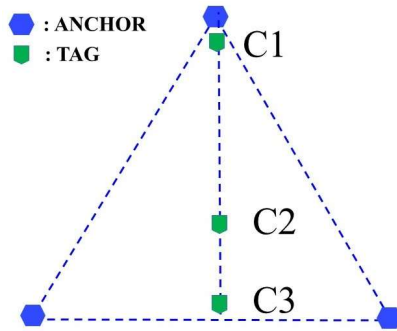


Fig. 10 Positions of the tags.

(d) Comparison of Factor Effects: In this part of the experiment, three factors with A, B, and C were used, respectively. A total of 18 sets of experiments were conducted with these three factors in combination. Finally, the signal-to-noise ratio (S/N) was used to compare the impact of each factor at different levels, and the experimental results are shown in Fig. 11. The higher the S/N ratio of level, the better the influence of position accuracy. From the figure, it can be seen that the impact of horizontally placed tags (A1) is greater than that of vertically placed tags (A2). This is because the UWB signals used for localization are more effective when they propagate parallel to the ground surface. When the tag is placed horizontally parallel to the floor, the UWB signals can propagate directly along the ground plane, minimizing reflections and multipath effects. This results in a more accurate and reliable measurement of the distance between the tag and the anchor nodes. On the other hand, when the tag is placed vertically, the UWB signals propagate in a direction perpendicular to the ground surface. This can introduce additional reflections and multipath effects from surrounding objects and surfaces, leading to inaccuracies in distance measurements and consequently reducing the overall positioning accuracy. Therefore, placing the tag horizontally

parallel to the floor in a UWB system allows for better positioning accuracy by minimizing the impact of reflections and multipath effects, resulting in more reliable and precise localization. Regarding tag placement height, the impact is higher at a height of 180 cm (B3) than at 140 cm (B2) and 100 cm (B1). This is because the positioning tag at a height of 180 cm is closer to the positioning base and less affected by ground items and signals, resulting in better signal reception. In terms of placement position, the C2 position, where the three anchors are equidistant, is the best because this position has more equidistant information, leading to smaller positioning calculation errors. The average positioning errors under these combinations are shown in Table V.

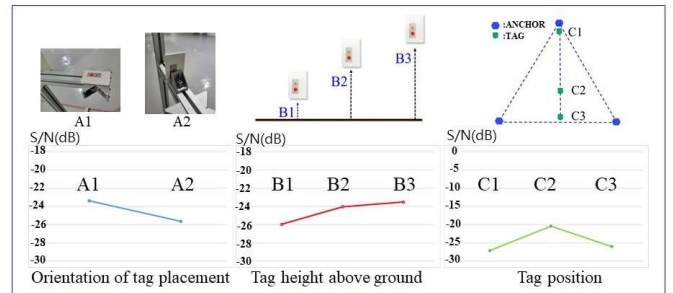


Fig. 11 The effect of the tags.

TABLE V
THE AVERAGE POSITIONING ERRORS OF THE TAGS

Number	A. Tag placement direction A1: Horizontal A2: Vertical	B. Tag placement height B1: 100 cm B2: 140 cm B3: 180 cm	C. Tag spacing C1 X: 1200cm, Y: 100cm Z: 100cm C2: X: 1200cm, Y: 1386cm Z: 100cm C3 X: 1200cm, Y: 1978cm Z: 100cm	Average error (cm)
1	A1	B1	C1	24.4
2	A1	B1	C2	10.5
3	A1	B1	C3	22.5
4	A1	B2	C1	18.1
5	A1	B2	C2	5.8
6	A1	B2	C3	22.7
7	A1	B3	C1	20.9
8	A1	B3	C2	6.2
9	A1	B3	C3	12.7
10	A2	B1	C1	29.5
11	A2	B1	C2	12.7
12	A2	B1	C3	24.0
13	A2	B2	C1	23.1
14	A2	B2	C2	15.2
15	A2	B2	C3	16.6
16	A2	B3	C1	20.4
17	A2	B3	C2	13.4
18	A2	B3	C3	21.6

IV. COMPARISON OF INSTALLATION METHODS.

In terms of anchor deployment testing, the target error was less than 30 cm, using (a) five anchors and (b) six anchors as shown in Fig. 12. The system origin (0,0) was set at the red dot near the corner on the upper left side. The purpose of using five anchors was to achieve a large-scale positioning system with fewer anchors, which could reduce equipment costs while achieving high positional accuracy. On the other hand, the advantage of using six anchors was that all the anchors were deployed around the working walls, which would not affect the existing space of manufacturers and provide an additional anchor signal to assist the tag in distance and accuracy calculation. Therefore, under the two deployment methods, 21 tag positions were set up, each with 30 data points measured, and the data was updated every second, tag position as shown in Fig. 13 and Fig. 14.

The corresponding positional accuracy under different positional factors was observed accordingly, as shown in Fig. 15 and Fig. 16. T5 to T8 and T16 to T19 were positions near the cement pillars, which aimed to confirm the effect of the tag's inability to receive the nearest anchor signal directly on the positional accuracy.

The Fig.13 indicates that the use of a 5-anchor setup for the system installation may reduce the number of anchors and potentially enhance signal reinforcement with the central anchor. However, the measurement results clearly show that the 5-anchor configuration is not superior, with a position accuracy ranging from 8.0 to 490.2 cm. where the average error and standard deviation are 55.6 cm and 102.7 cm respectively. On the other hand, the 6-anchor sensing method demonstrates the best position accuracy with a range of 5.4 to 29.8 cm. where the average error and standard deviation are 22.6 cm and 6.2 cm respectively. Despite the potential advantages of using fewer reference anchors and obtaining unobscured distance signals due to the central anchor, the 5-anchor setup is more prone to calculation errors and therefore less likely to achieve high position accuracy.

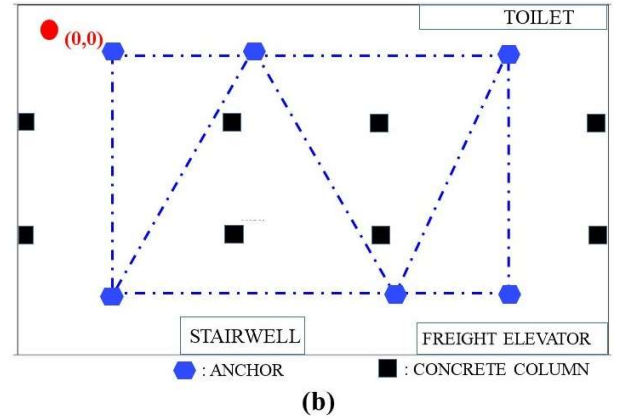
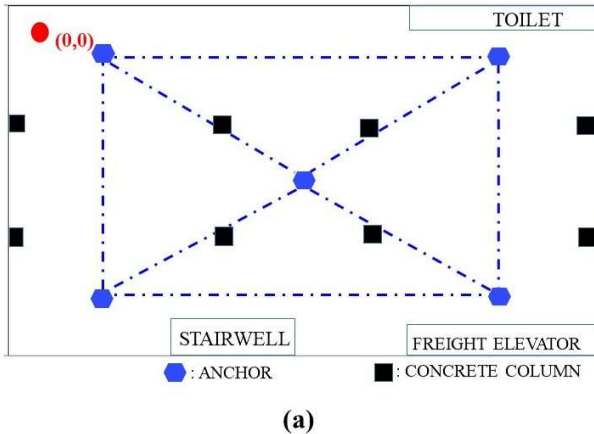


Fig. 12 The configuration of the (a) the five anchors and (b) the six anchors.

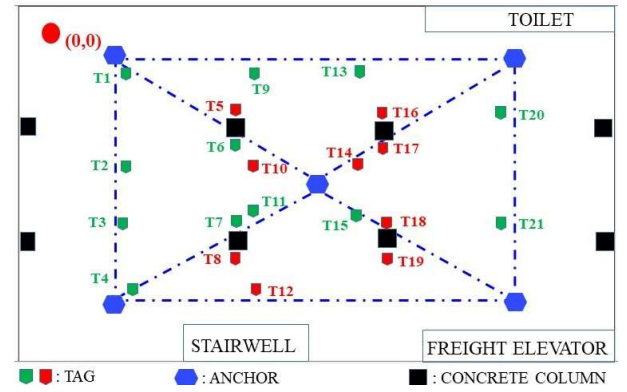


Fig. 13 Tag distribution under the five anchors configuration.

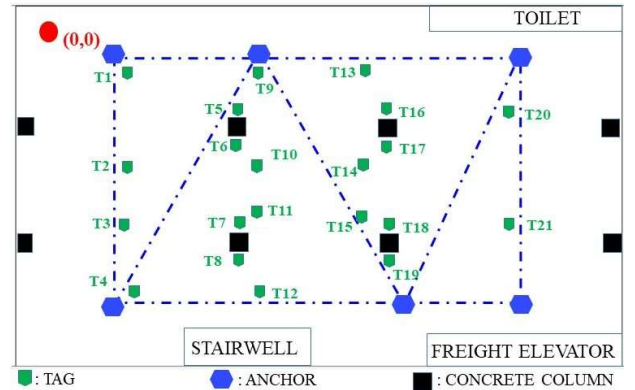


Fig. 14 Tag distribution under the six anchors configuration.

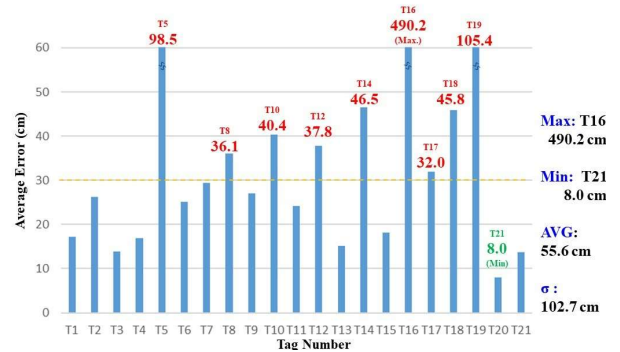


Fig. 15 Positioning error under the five anchors configuration.

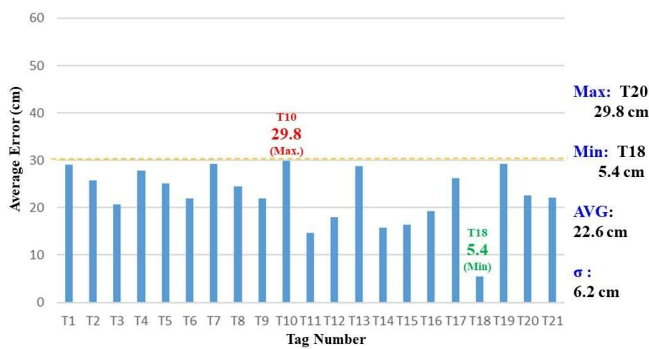


Fig. 16 Positioning error under the six anchors configuration.

V.CONCLUSION

In this paper, a method is proposed for finding optimal anchor placement, compensating for tag positioning error, and determining the maximum range of two different UWB system setups to enhance UWB-based positioning and localization. The results are validated through numerical analysis to optimize the measurement outcomes. The proposed technique does not require additional sensors or learning algorithms such as particle filters or deep learning, nor does it require prior knowledge of UWB tag positions or accurate ground truth measurement equipment. Furthermore, the proposed method is tested in a complex factory environment, addressing all factors that cause multipath and NLOS effects. This study implements the trilateration principle combined with time-of-flight (TOF) to measure the tag position. A generalized experimental configuration is selected with six positioning base stations within an area of 34.3 m x 24.5 m. The positioning accuracy is evaluated by measuring positions at 21 different locations, demonstrating an average accuracy of 22.6 cm. These findings highlight the potential of UWB technology to achieve high-precision indoor localization, making it a promising solution for automation and smart factory applications.

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Wei-Ming Chen, Ph.D., received the Ph.D. degree in mechanical engineering from National Chiao Tung University, Taiwan, in 2013. Since 2022, he has been a mechanical engineer in department of robotic technology, Precision Machinery Research & Development Center, Taichung City, Taiwan. His research interests include mechanical design, and positioning technology.



Tesfaye Wakessa Gussu, Ph.D., received the Ph.D. degree in mechanical engineering from National Taiwan University of Science and Technology, Taiwan, in 2017. Since 2021, he has been a mechanical engineer in department of robotic and AVG technologies, Precision Machinery Research & Development Center, Taichung City, Taiwan. His research interests include mechatronic system design, Mobile robots positioning and localization.



Yan-Ru Lai, MS., degree in Departments from Mechanical Engineering from National Kaohsiung University of Applied Sciences, Kaohsiung City, Taiwan, in 2016. From 2017 to 2023, she was a Deputy Director of the Robotics & Automation Division. she has been a mechanical engineer, Precision Machinery Research & Development Center, Taichung City, Taiwan. Her research interests include Controller Design, Robot system Integration.



Che-Chien Chen, MS., *degree in Departments from Mechanical Engineering from Chang Gung University, Taoyuan City, Taiwan, in 2008* , Since 2021, he has been a mechanical engineer in department of robotic and AVG technologies, Precision Machinery Research & Development Center, Taichung City, Taiwan. His research interests include Mechanical Design, Robot system Integration.