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Performance Analysis of UWB Localization in Multi-Floor Industrial Scenarios

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Abstract— In industrial environments, precise operator localization is a critical challenge to enhance safety, particularly in confined spaces or hazardous zones requiring rapid interventions. While the Global Positioning System is widely utilized, it is unsuitable for indoor environments. An alternative solution lies in the use of radio frequency devices, with Ultra-Wideband (UWB) technology emerging as one of the most promising methods for precise indoor localization. However, industrial environments raise additional challenges, such as the presence of obstacles that lead to non-line-of-sight (NLOS) conditions and complex spatial configurations. This paper investigates the application of UWB-based localization in multi-floor environments, focusing on the impact of anchor placement on localization accuracy. Through experimental studies, it is demonstrated that UWB enables precise localization, even in complex configurations involving multiple floors or independent zones. Furthermore, this study highlights the importance of exploring anchor placement optimization while accounting for NLOS effects, paving the way for significant improvements in localization performance within complex industrial environments.

Keywords-component; Ultra-Wideband; Indoor Localization; Multi-floor environment; Industrial environments; Performance analysis

I. Introduction

Indoor localization represents a fundamental research domain, particularly in complex industrial environments where the Global Positioning System is unsuitable due to its inability to function effectively in enclosed or covered spaces. This growing interest aligns with the principles of Industry 5.0, which aims to integrate process automation, enhanced safety, and operator well-being [1].

From an operational perspective, many modern factories are adopting advanced technologies such as autonomous robots and drones [2]. These systems require precise spatial localization to function properly. For instance, drones deployed for surveillance or inspection tasks must navigate accurately among obstacles while following precise trajectories to avoid collisions [3]. Consequently, ensuring robust indoor localization is a key factor in guaranteeing both the efficiency and safety of these tools.

Beyond automation, indoor localization also plays a critical role in improving safety within industrial environments [4]. Technologies such as radio frequency (RF) anchors, particularly Ultra-Wideband (UWB) devices [5], have demonstrated their ability to meet the growing demands for indoor localization. In industrial settings, precise localization offers several benefits. It can, for example, guide operators to specific locations while ensuring their safety. Furthermore, dynamic safety zones can be established around equipment to protect operators. These zones also enable the automation of machinery shutdowns in case of zone violations, significantly reducing the risk of serious accidents [6]. Some systems already combine UWB with intelligent management of hazardous zones, enhancing both safety and operational efficiency [7].

To meet stringent safety standards, localization systems must deliver high accuracy in complex and dynamic indoor environments. UWB is recognized as a high-performance localization technology. However, non-line-of-sight (NLOS) conditions, which are common in cluttered industrial environments, remain a major source of error despite UWB signals' ability to penetrate certain materials [8]. Various approaches have been proposed to mitigate these limitations, including optimizing anchor placement, and developing advanced signal processing techniques [9]. However, these existing approaches have not been tested in multi-story environments.

II. Related Works

To ensure accurate localization in RF-based systems, particularly those using UWB, numerous studies have focused on optimizing anchor placement to maximize accuracy performance in practical environments [3, 10–16]. These efforts aim to achieve three main objectives: minimizing localization errors, improving coverage, and reducing installation costs by decreasing the number of required anchors. These studies often leverage evolutionary algorithms to determine optimal anchor configurations, ensuring a balance between accuracy and deployment cost [3]. While some studies have extended their analyses to three-dimensional (3D) environments [3, 15, 16], they generally remain limited to homogeneous spaces without accounting for multi-story environments. This gap is particularly significant, as the vertical dimension plays a crucial role in complex industrial environments where floors introduce substantial obstacles to UWB signal propagation.

The growing interest in 3D indoor localization has led to the exploration of various technologies, such as Wi-Fi, Bluetooth, and inertial measurement units (IMUs) [17]. However, these approaches present notable limitations in industrial environments. IMUs, for example, suffer from cumulative drift that compromises long-term accuracy, particularly in spaces where precise measurements are essential. Although Wi-Fi and Bluetooth are widely available, they fail to achieve sub-meter accuracy, especially in the presence of multiple obstacles. In contrast, UWB is a technology recognized for its superior precision in complex indoor environments [18]. However, its application in multi-story scenarios remains underexplored. One study used a combination of UWB and a barometer to improve floor detection [19]. While promising, this approach relied on a fingerprinting method based on received signal strength. However, fingerprinting presents several drawbacks in industrial contexts: it requires a large database to be built and maintained, and any environmental change (e.g., machine reorganization) necessitates a complete update of the database [20]. These constraints represent a significant workload in dynamic environments.

Finally, although there are several studies on optimizing anchor positioning in 3D environments, none specifically address multi-story scenarios. The absence of research integrating multilateration in multi-story environments is another significant gap. Multilateration offers potential advantages over fingerprinting, including increased accuracy without the need for large databases. However, its use remains unexplored in these contexts, despite its promise to overcome the challenges associated with localization in complex industrial environments.

To address the gaps identified in the literature, this research proposes a comprehensive analysis of UWB technology performance in multi-story industrial environments. The main contributions are as follows:

- **Understanding the impact of floors on UWB measurements:** Floors can significantly affect UWB distance measurements, introducing errors that compromise localization accuracy. Studying this impact helps to better characterize signal propagation in multi-floor environments and anticipate potential biases in positioning systems.
- **Assessing feasibility of multilateration across floors**: This study examines whether UWB localization can be achieved by placing anchors only on a lower floor and investigates if this placement negatively affects accuracy on higher floors.
- **Investigating the relationship between accuracy, anchor placement, and quantity:** The accuracy of UWB localization depends not only on the number of anchors but also on their spatial configuration. By exploring different placement strategies, this study identifies key factors that enhance positioning precision in multi-floor environments.
- **Advancing 3D localization strategies for complex environments:** Addressing the challenges of multi-story localization is crucial for improving operator tracking and automation in industrial settings. This research contributes to refining UWB-based positioning by offering guidelines to mitigate errors and enhance system reliability.

III. METHODOLOGY

The methodology employed in this study is organized into five distinct stages, each contributing to a comprehensive evaluation of the UWB-based localization system. First, we describe the hardware used in our experiments (A), which provides the foundation for the localization setup. Next, we explain the Two-Way Ranging (TWR) technique (B) for distance estimation. This is followed by an analysis of the errors induced by materials and obstacles in the environment (C). The fourth stage (D) introduces the multilateration process, which is employed to calculate the position of the tracked device based on the distance estimates. Finally, the experimental environment is detailed (E), offering context to the setup and the conditions under which the system's performance is tested.

A. Qorvo DWM1001-DEV

For this study, the DWM1001-DEV device, developed by Qorvo [21], was used to conduct the experiments. This module relies on UWB technology, known for its high accuracy in distance and indoor positioning measurements. For the purposes of this research, the module was configured to perform distance measurements at a frequency of 5 Hz, allowing for precise tracking of moving targets in complex environments. This frequency ensures an optimal balance between temporal precision and measurement stability, while also reducing power consumption constraints.

B. TWR Estimations

The distance measurements made by the DWM1001-DEV module rely on the TWR method, widely used in UWB systems to estimate the distance between two devices. This technique relies on the exchange of time messages between a transmitter and a receiver. TWR is an indirect method to estimate the Time of Flight (TOF), which is the time it takes for a signal to travel the distance d between two devices at the speed of light c. The measured distance is defined in (1):

$$d = c \cdot TOF \tag{1}$$

Where d is the distance between the two devices. However, directly measuring the TOF requires very precise synchronization between the clocks of the devices, which is difficult to guarantee. TWR circumvents this problem by measuring the total round-trip time (T_{RTT}) and then compensating for the fixed delay introduced by the receiver (Δ_T). The TOF is extracted from TWR using (2):

$$TOF = \frac{T_{RTT} - \Delta_T}{2} \tag{2}$$

The distance d is then calculated with (1) and (2). This method avoids the need for strict synchronization between the clocks, as the calculation relies solely on locally measured times by the transmitter and receiver.

The distance measurement d_m between two UWB devices is influenced by the propagation of radio waves in the Fresnel zone, a region around the direct line of sight where waves scatter. This scattering, related to the physical properties of the signal, such as frequency, and thus wavelength λ, induces an error ϵ in the measurement. Hence, the measured distance is given by (3):

$$d_m = d_r + \epsilon \tag{3}$$

Where d_r is the true distance. The higher the frequency, the more sensitive the precision is to these effects.

C. *Error induced by Materials*

In NLOS conditions, the signal passes through a wall and is deflected. The deflection depends on the material's reflection index and may vary according to the dielectric constant of the obstacle. The round-trip time of emission and reception of the signal is thus modified, and the deviation of the measurement is presented in (4) and (5) as follows:

$$T_{RTT} = 2 \cdot \left(\frac{d + w \cdot (R-1)}{c} \right) \tag{4}$$

$$d' = d + w \cdot (R-1) + c \cdot \frac{-\Delta_T}{2} \tag{5}$$

Where d' is the measured distance and d is the actual distance between transmitter and receiver, w is the width of the obstacle and R is the refractive index of the material. The deflection of the UWB signal transmitted between two devices and its impact on distance measurement is illustrated in Figure 1. The actual signal path is compared to the deflected path, highlighting the resulting measurement error in the calculated distance.

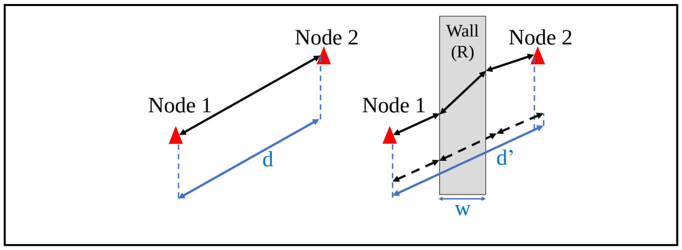

Figure 1. Illustration of the impact of UWB signal deflection by a material on the measured distance.

D. *Multilateration*

Multilateration is a positioning technique that uses distance measurements between a target object and several reference points, known as anchors. This method relies on the principle of triangulation, where the position of the object is determined by the intersection of several spheres centered on the anchors. In 3D, at least four non-coplanar anchors are required to determine a unique position. Each anchor A_i of coordinates (x_i,y_i,z_i) emits a signal that allows measuring the distance d_i between the anchor and the target object. The equation of the sphere around each anchor A_i is given by (6):

$$d_i^2 = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 \tag{6}$$

Where (x_i, y_i, z_i) are the coordinates of anchor A_i, and d_i is the distance measured between anchor A_i and the target object.

For four anchors $A_1, A_2, A_3\ et\ A_4$, the equations of the sphere are described in (7):

$$\begin{cases} d_1^2 = (x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 \\ d_2^2 = (x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 \\ d_3^2 = (x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 \\ d_4^2 = (x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2 \end{cases} \tag{7}$$

To determine the position of the target object, the system of equations formed by these four equations is solved. The intersection of the resulting spheres provides the estimated position of the target object, as shown in Figure 2.

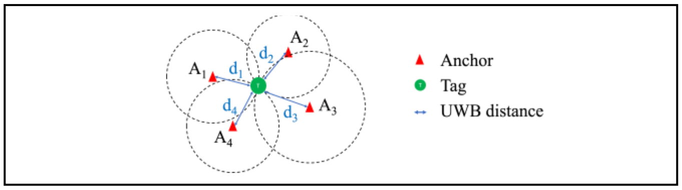

Figure 2. Schematic of multilateration with anchors (red) and a tag (green).

E. *Environment*

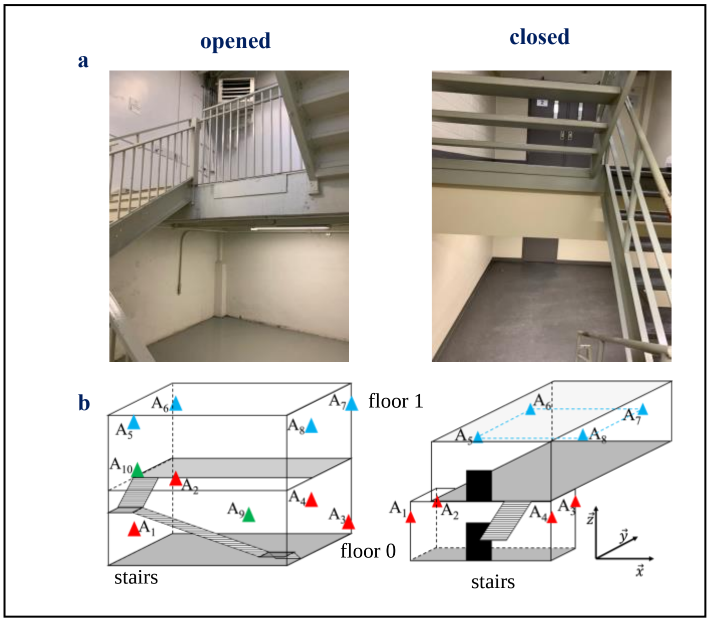

Figure 3. Presentation of the study environments. (a) Photographs of both experimental environments: opened, wirhout doors separating the two floors (left) and closed, with doors separating the two floors (right). (b) Schematic representation of UWB anchors arrangement within the environments.

TABLE I. COORDINATES OF ANCHORS IN OPENED (LEFT) AND CLOSED (RIGHT) ENVIRONMENTS

Anchor	X (m)	Y (m)	Z (m)	Anchor	X (m)	Y (m)	Z (m)
A_1	0,00	-2,43	2,11	A_1	0,00	-2,43	2,11
A_2	1,20	0,00	2,08	A_2	1,20	0,00	2,08
A_3	4,50	-2,16	2,15	A_3	4,50	-2,16	2,15
A_4	0,00	-2,52	5,10	A_4	0,00	-2,52	5,10
A_5	0,82	0,00	5,00	A_5	0,82	0,00	5,00
A_6	0,82	0,00	5,00	A_6	0,82	0,00	5,00
A_7	4,12	0,00	5,10	A_7	4,12	0,00	5,10
A_8	4,50	-2,53	5,10	A_8	4,50	-2,53	5,10
A_9	3,72	-6,11	2,90				
A_{10}	0,39	-6,10	4,20				

The experiments were conducted in two distinct environments, referred to as "open" when there are no doors separating the spaces, and "closed" when doors divide the areas. Figure 3 provides an overview of these environments and the positioning of the UWB anchors. Figure 3.a presents photographs of the two experimental environments: the open environment on the left and the closed environment on the right. Figure 3.b offers a schematic representation of the spatial arrangement of the UWB anchors within the environments, illustrating their placement across different floors and areas. Finally, Table II provides a table listing the precise coordinates (x, y, z) of each anchor, offering a detailed mapping of their spatial distribution.

IV. EXPERIMENTATION

This section presents the experimental results of our study on UWB multilateration in multi-floor environments. The experiments are divided into three main parts: the impact of the floor on UWB distance measurement, trajectory tracking in a multi-story environment, and the optimization of tracking through the addition of anchors. These experiments aim to evaluate the accuracy, coverage, and robustness of UWB-based localization systems in complex indoor settings. To provide a comprehensive overview of our findings, Figure 5 summarizes the key results of our experiment. Figure 4 illustrates the effect of a concrete floor on UWB distance measurement by comparing line of sight (LOS) and NLOS conditions using boxplots. Figure 5.a shows the actual trajectory of the operator, which serves as the reference for trajectory tracking experiments. Figure 5.b presents the results of a multilateration test using four anchors (A_1 to A_4) positioned on floor 0, while Figure 5.c demonstrates trajectory tracking in a multi-floor environment using eight anchors. Figure 5.d displays a representative trajectory followed by the operator with eight anchors, and Figure 5.e highlights the improvements in trajectory accuracy when using nine and ten anchors. Finally, Table II provides a summary table of localization accuracy across different zones in the environment, offering a comprehensive overview of the system's performance.

A. *Impact of the Floor on UWB Distance Measurement*

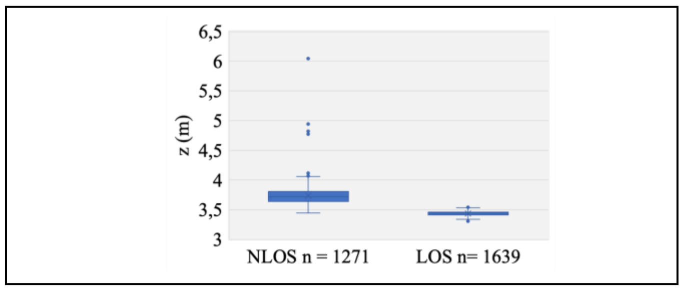

Figure 4. Dispersion of UWB distance measurement in the same environment with and without the floor as an obstacle (NLOS vs. LOS).

To evaluate the impact of a floor on the distance measurement between two UWB devices, measurements were taken in the same environment (Figure 3.a opened), both with and without the presence of a floor directly obstructing the LOS between the devices. Figure 4 illustrates the observed deviations. The results demonstrate that thick concrete floors significantly degrade UWB localization accuracy due to their high dielectric constant, which alters signal propagation. Compared to a LOS condition, the presence of a concrete floor increased the mean localization error from 4 cm to 26 cm and the standard deviation from 3.3 cm to 14.3 cm, representing a fourfold increase in variability. This confirms that non-uniform materials introduce substantial NLOS errors, reducing multilateration reliability.

B. Trajectory Tracking in a Multi-Story Environment

In a multi-story environment (open or enclosed), we evaluated the feasibility of localization through multilateration. To assess the ability to track an operator, the UWB tag was placed on the operator's head, in accordance with the recommendations of [22], which minimize NLOS conditions relative to the anchors. The paths followed in the two environments are shown in Figure 5.a.

Initially, the study focused on localizing the operator across two areas, corresponding to levels 0 and 1, as shown in Figure 3.b. The operator’s position was determined using only four anchors located on level 0, as illustrated in the environment of Figure 3.b. Using only four anchors located on the ground floor proved insufficient for multi-floor localization as depicted in Figure 5.b. Due to NLOS conditions introduced by the concrete floor, the distance estimations were too inaccurate to allow for successful multilateration on the upper floor. The errors in distance measurements prevented the formation of well-defined intersection points required for precise positioning, leading to unreliable or missing location data on the upper floor.

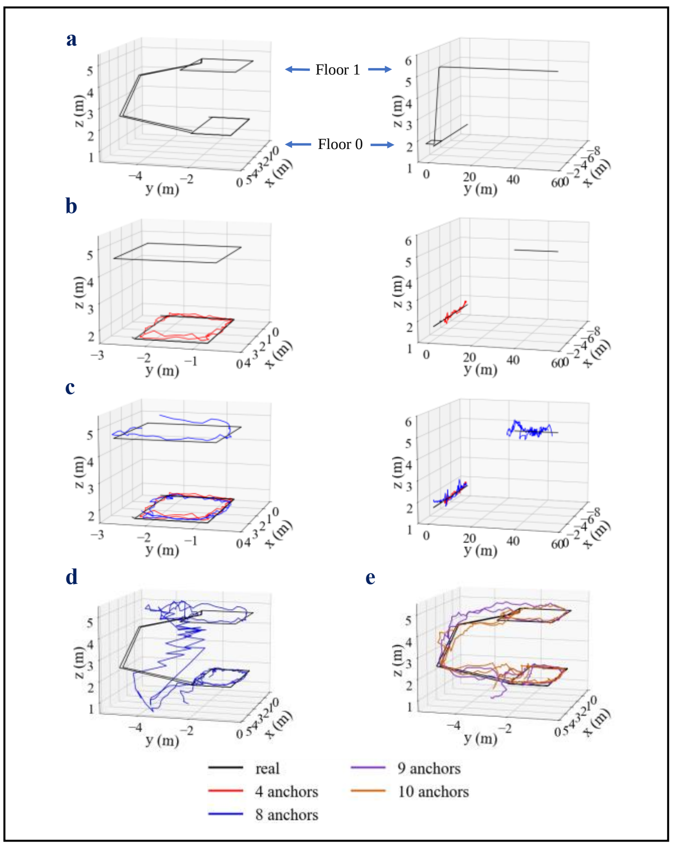

Figure 5. Experimental results on the accuracy and coverage of UWB multilateration in a multi-floor environment. (a) Actual trajectory of the operator recorded as the reference in opened (left) and closed (right) environments. Multilateration test using 4 anchors (A_1 to A_4) positionned on floor 0 (b), using 8 anchors (A_1 to A_8) (c) in opened (b, c left) and closed (b, c right). environments. Trajectory followed by the operator with 8 anchors (d) and with 9 and 10 anchors (e) in opened environment.

TABLE II. SUMMARY OF LOCALIZATION ACCURACY ACROSS DIFFERENT ZONES IN THE OPEN ENVIRONMENT

Anchors	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Coverage floor 0 (%)	100	100	100	100	100	100	100
Accuracy floor 0 (cm)	10,4	11,6	11,0	9,8	10,6	9,4	10,8
Coverage stairs (%)	23	40	34	40	48	100	100
Accuracy stairs (cm)	277,3	219,2	226,2	209,4	178,8	22,3	21,2
Coverage floor 1 (%)	0	20	68	70	100	100	100
Accuracy floor 1 (cm)	/	57,8	51,6	19,2	11,7	11,9	12,0

This result can be explained by the errors in NLOS distance measurements through the concrete floor. These measurements, affected by significant errors, do not produce intersecting spheres converging to a unique point. Consequently, operator localization cannot be achieved across multiple levels with only four anchors. These observations highlight the need to consider adapted anchor configurations to ensure multi-story spatial coverage, particularly in complex industrial environments. Subsequently, we tested operator localization by adding four anchors to the upper level.

The measured trajectories with eight anchors are illustrated in Figure 4.c. In the open environment, positions were detected on both levels and corresponded to the actual path taken, with an average positioning error of 11.4 cm (Figure 5.c). Measurement repeatability was confirmed in a second (closed) environment characterized by UWB signal drop zones. The results indicate that position tracking is feasible in different contexts, even when independent systems must take over to ensure coverage of distinct environments (Figure 5.c). The results presented in Figure 5.d show that staircases present a particular challenge for UWB-based localization. The accuracy is significantly degraded due to the multiplication of NLOS conditions caused by the positioning of anchors relative to staircases. This results in an increased localization error, with a mean deviation of 1.78 m and only 48% coverage. The non-uniform spatial distribution of the anchors, combined with obstructions due to stair railings and steps, contributes to a weaker signal reception and higher measurement variability.

C. Optimization of Tracking Through Additional Anchors

To enhance accuracy in complex areas, particularly staircases a new set of experiments was conducted by adding additional anchors. Figure 4.e illustrates that adding one anchor, A_9, significantly improved coverage and accuracy, reducing the root mean square error to 22 cm. A similar result was achieved by adding another anchor, A_{10}, which allowed for 100% coverage of trajectories within the staircases. The experimental results confirm that reducing the number of anchors negatively impacts localization coverage and accuracy. When using only seven anchors instead of eight, the coverage on the upper floor dropped to 70%, and the mean localization error increased from 12 cm to 19 cm (Table II). This degradation highlights the importance of maintaining a sufficient number of well-positioned anchors to ensure reliable multi-floor tracking.

V. Conclusion

This study analyzed the impact of environmental conditions on the accuracy of UWB localization, emphasizing the challenges posed by multi-story industrial environments and NLOS conditions. The results demonstrate that thick concrete floors significantly increase measurement errors and reduce the reliability of multilateration, leading to major inaccuracies in distance estimation. A standard four-anchor configuration proves insufficient for multi-story localization, as NLOS distance measurements fail to provide a unique intersection point for positioning.

To address these limitations, optimizing both the number and placement of UWB anchors is essential. The strategic addition of anchors significantly improves localization accuracy, particularly in complex areas such as staircases, achieving 100% coverage and reducing tracking error to 11 cm. These findings underscore the importance of careful UWB deployment to ensure reliable operator tracking in industrial environments.

This study paves the way for several future research directions. A more refined modeling of the interactions between the UWB signal and obstacles could help anticipate and correct errors caused by NLOS conditions. Furthermore, the development of optimization algorithms based on machine learning could offer automated solutions for determining ideal anchor configurations based on the geometry and specific constraints of each environment.

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