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Development of a UWB-Based Trilateration System for Multi-Mobile Node Indoor Localization

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Abstract – *Accurate indoor localization is essential for navigation and coordination in multi-agent systems, particularly in environments where Global Positioning System (GPS) signals are unavailable. While ultrawideband (UWB)-based trilateration has been widely studied, most existing works focus on single-node localization and do not explicitly address scalability in terms of computational cost and processing time. This study proposes a scalable multi-mobile node localization framework based on UWB trilateration, with a key contribution in demonstrating linear computational growth with respect to the number of mobile nodes. The system employs UWB DWM1000 modules and the Symmetrical Double-Sided Two-Way Ranging (SDS-TWR) method to estimate distances between mobile nodes and anchor nodes, followed by onboard trilateration for position estimation. Experimental validation is conducted using up to four simultaneous mobile nodes within a 10×10 m indoor environment. The results show that the proposed system maintains centimeter-level accuracy, with RMSE values of 10.08 cm, 11.46 cm, 12.25 cm, and 9.13 cm for nodes 1 to 4, respectively. More importantly, the processing time increases consistently from 55 ms (one node) to 115 ms (four nodes), exhibiting an approximately constant incremental cost of 20 ms per additional node, which confirms the linear scalability of the proposed approach. These findings highlight that the proposed system not only achieves reliable localization accuracy but also ensures predictable and efficient computational performance, making it suitable for real-time multi-node applications such as robot swarm coordination and collaborative autonomous systems.*

***Keywords**: trilateration, localization, multi node, ultrawideband DWM1000.*

I. Introduction

Accurate indoor localization has become an essential component in modern navigation systems, particularly in environments where Global Positioning System (GPS) signals are unavailable or unreliable. Indoor positioning technologies have therefore received significant attention in recent years due to their applications in robotics, logistics automation, industrial monitoring, smart buildings, and autonomous navigation systems. Among the various technologies available for indoor localization, ultra-wideband (UWB) has emerged as one of the most promising solutions due to its high positioning accuracy, low latency, and robustness against multipath interference [1], [2].

UWB-based localization systems estimate the position of an object by measuring the propagation time of radio signals between transmitter and receiver nodes. Several ranging techniques have been developed for UWB localization, including Time of Arrival (ToA), Time Difference of Arrival (TDoA), and Two-Way Ranging (TWR) methods [3], [4]. These measurements are then used by geometric algorithms such as trilateration or multilateration to estimate the coordinates of mobile nodes relative to anchor nodes with known positions [5]. Trilateration remains one of the most widely used methods because of its relatively simple implementation and computational efficiency, making it suitable for real-time applications [6].

The development of UWB localization technology has been accelerated by the availability of commercial modules such as Decawave DWM1000, which provide centimeter-level ranging accuracy and support low-power wireless communication [7]. These modules enable researchers to implement practical indoor localization systems without the need for complex RF hardware design. Several studies have demonstrated the feasibility of using DWM1000 modules for indoor positioning systems with high accuracy and real-time performance [8].

In robotics applications, indoor localization plays a crucial role in enabling autonomous navigation and coordination among multiple robots. UWB localization has been successfully applied to mobile robot navigation systems, where position estimates are obtained using particle filters, Kalman filters, or geometric approaches combined with UWB ranging data [9]. For example, González et al. demonstrated that UWB-based localization combined with particle filtering can significantly improve mobile robot positioning accuracy in indoor environments [1]. Similarly, Segura et al. compared several localization techniques and showed that UWB-based systems provide reliable positioning performance for robotic navigation tasks [2].

One important research direction in recent years is the development of multi-node localization systems, which allow simultaneous tracking of multiple mobile devices or robots within a shared environment. Such systems are essential in applications such as robot swarm coordination, collaborative robotics, and warehouse automation [10]. In swarm robotics, each robot must continuously obtain accurate position information to maintain formation stability and perform cooperative tasks effectively [11]. Therefore, localization systems must provide not only high accuracy but also fast update rates and scalability as the number of nodes increases.

Despite the advantages of UWB technology, several challenges remain in practical indoor environments. One of the most significant issues is Non-Line-of-Sight (NLOS) propagation, which introduces bias errors in distance measurements due to signal obstruction or reflection [12]. Various techniques have been proposed to mitigate NLOS errors, including machine learning-based classification, anchor-based correction methods, and hybrid sensor fusion approaches [13], [14]. These approaches aim to improve localization accuracy by identifying and compensating for NLOS measurement errors before or after the position estimation process.

Another promising research direction involves sensor fusion, where UWB localization is combined with other sensing technologies such as inertial measurement units (IMU), visual odometry, LiDAR, or wheel odometry [15], [16]. By integrating multiple sensor modalities, these systems can achieve improved robustness and reliability, particularly in dynamic environments where individual sensors may suffer from measurement degradation.

In addition, several studies have investigated optimization techniques for improving UWB localization accuracy. These include anchor placement optimization, error map modeling, adaptive filtering methods, and machine learning approaches [17]–[19]. These techniques aim to reduce positioning errors caused by multipath propagation, clock synchronization errors, and measurement noise.

Recent studies have also explored the scalability of UWB localization systems for multi-robot and multi-tag scenarios. Mesh network architectures and collaborative localization frameworks have been proposed to enable efficient communication and positioning among multiple nodes [20], [21]. These systems allow multiple mobile nodes to estimate their positions simultaneously while maintaining acceptable computational complexity and communication overhead.

Although significant progress has been made in UWB-based localization systems, several research gaps remain. Many existing studies focus primarily on single-node localization or do not evaluate the impact of increasing node numbers on localization accuracy and processing time. In real-world applications such as swarm robotics or collaborative autonomous systems, the localization system must maintain both high accuracy and low latency while supporting multiple mobile nodes simultaneously. Therefore, further investigation is needed to evaluate the trade-off between positioning accuracy, scalability, and computation time in multi-node localization systems.

Based on these considerations, this study investigates the implementation of a multi-mobile node localization system using the trilateration method with the UWB DWM1000 module. The proposed approach aims to evaluate the localization performance in terms of positioning accuracy and processing time when multiple mobile nodes are tracked simultaneously. Such a system is expected to provide a practical and cost-effective solution for indoor navigation and multi-robot coordination applications.

II. Method

To implement the trilateration-based localization method, a minimum of three anchor nodes and one mobile tag node are required to estimate the position of an object in the two-dimensional (x, y) plane. In this configuration, the anchor nodes are placed at predetermined coordinates, while the tag node represents the unknown position to be estimated. An optimal deployment is achieved when the anchor nodes are arranged in a triangular configuration within a square localization area, as illustrated in Fig. 1, which improves geometric stability and positioning accuracy.

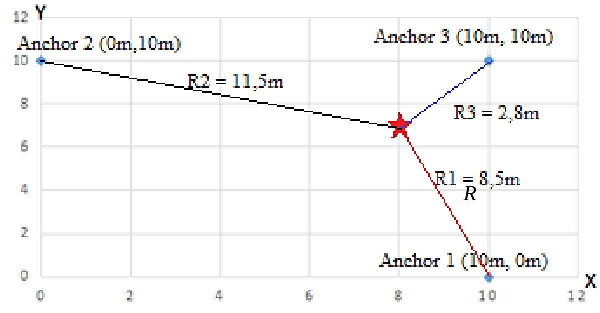

Fig. 1. Anchors position for trilateration method.

A. *Symmetrical Double Sided-Two Way Ranging Method* (SDS-TWR)

The localization process begins by measuring the distances between the mobile tag node and each anchor node. These distance measurements are obtained using the SDS-TWR technique, which estimates the signal propagation time by calculating the difference between the transmission time and the reception time of exchanged packets between nodes [22], as illustrated in Fig. 2.

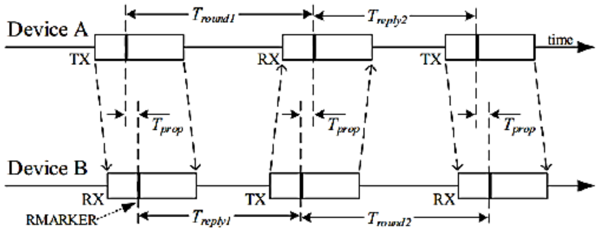

Fig. 2. Timing diagram of the Symmetrical Double Sided-Two Way Ranging method used to estimate the signal propagation time between two UWB nodes.

In this study, the distance between two nodes is measured using the SDS-TWR implemented on the UWB DWM1000 module. This technique estimates the signal propagation time without requiring strict clock synchronization between devices. In the SDS-TWR protocol, two nodes exchange three messages sequentially: poll, response, and final. Device A first transmits a poll message to Device B. After receiving the signal, Device B sends a response following a predefined reply delay. Device A then transmits the final message after another delay. During this exchange, both devices record the round-trip times and reply delays. The signal propagation time T_{prop} can be expressed as

$$T_{prop} = \frac{(T_{round1} \times T_{round2}) - (T_{reply1} \times T_{reply2})}{T_{round1} + T_{round2} + T_{reply1} + T_{reply2}} \quad (1)$$

Finally, the distance between the two nodes is calculated using

$$R = c \times T_{prop} \quad (2)$$

Where R denotes the distance between the nodes, c is the speed of light (299792458 m/s). The SDS-TWR method improves ranging accuracy by compensating for clock drift and processing delays between devices.

B. *Trilateration*

Based on the measured distances and the known coordinates of the anchor nodes, the trilateration algorithm is applied to compute the estimated coordinates of the mobile node. The overall localization framework implemented in this study is illustrated in Fig. 1.

The position of the mobile node in the two-dimensional (x, y) plane is estimated by the microcontroller embedded in the mobile tag node using the trilateration method [23]. To perform the trilateration computation, several parameters are required, including the known coordinates of the three anchor nodes, namely Anchor1 (x_1, y_1) Anchor2(x_2, y_2), and Anchor3 (x_3, y_3). In addition, the distance measurements between the mobile node carrying the tag node and each of the anchor nodes are required. These distances are represented as R1, R2, and R3, corresponding to the distances from the mobile node to Anchor1, Anchor2, and Anchor3, respectively. Furthermore, the position of mobile node (x, y) can be calculated by solving the following equations:

$$R_i^2 = (x_i - x)^2 + (y_i - y)^2, \quad i = 1, 2, 3 \quad (3)$$

Rewriting Eq. 3 in matrix form, we have:

$$\begin{bmatrix} 2(x_2 - x_1) & 2(y_2 - y_1) \\ 2(x_3 - x_1) & 2(y_3 - y_1) \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} R_1^2 - R_2^2 - x_1^2 + x_2^2 - y_1^2 + y_2^2 \\ R_1^2 - R_3^2 - x_1^2 + x_3^2 - y_1^2 + y_3^2 \end{bmatrix} \quad (4)$$

Solving Eq. 4, the coordinate (x, y) is obtained as follows:

$$\begin{cases} \begin{bmatrix} x \\ y \end{bmatrix} = A^{-1} b \\ A = \begin{bmatrix} 2(x_2 - x_1) & 2(y_2 - y_1) \\ 2(x_3 - x_1) & 2(y_3 - y_1) \end{bmatrix} \\ b = \begin{bmatrix} R_1^2 - R_2^2 - x_1^2 + x_2^2 - y_1^2 + y_2^2 \\ R_1^2 - R_3^2 - x_1^2 + x_3^2 - y_1^2 + y_3^2 \end{bmatrix} \end{cases} \quad (5)$$

C. *Experimental Setup*

To evaluate the performance of the proposed localization method, experiments were conducted using UWB DWM1000 modules. Three anchor nodes were deployed at fixed and known coordinates, arranged in a triangular configuration as illustrated in Fig. 1. This configuration was selected to ensure stable geometric conditions for the trilateration algorithm. Four mobile robot platforms were used as mobile nodes, each equipped with a UWB tag module. The robots were designed to move within a 10×10 m experimental area, as shown in Fig. 3.


(a) (b)

Fig. 3. Experimental setup: a. 4 mobile nodes within 3 anchors; b. design of the mobile node.

During the experiments, each mobile node performed distance measurements to the three anchor nodes using the

Symmetrical Double-Sided Two-Way Ranging (SDS-TWR) protocol implemented in the DWM1000 module. The measured distances were then processed by the onboard microcontroller to estimate the position of each mobile node using the trilateration algorithm. The localization performance was evaluated in terms of position estimation accuracy and processing time, particularly as the number of active mobile nodes increased. The detailed experimental setup conditions are presented in Table I.

TABLE I
EXPERIMENTAL SETUP

Parameter	Specification
Technology	UWB (DWM1000)
Method	SDS-TWR and Trilateration
Dimension	2D
Anchors	3 (fixed, triangular)
Mobile nodes	Up to 4
Area	10 m x 10 m

III. Experimental Results and Discussion

Initial testing was conducted to validate the performance of the DWM1000 module in distance measurement. Three DWM1000 devices configured as anchors and one mobile node were evaluated under line-of-sight (LoS) conditions without obstacles. The characteristics of the measurement results are presented in Fig. 4. The average total root-mean-square error (RMSE) of each measurements are 4.4 cm, 2.7cm, 3.5 cm and standard deviations (StD) are 2.6, 3.8, and 4.9 for anchor1, anchor2, and anchor3, respectively.

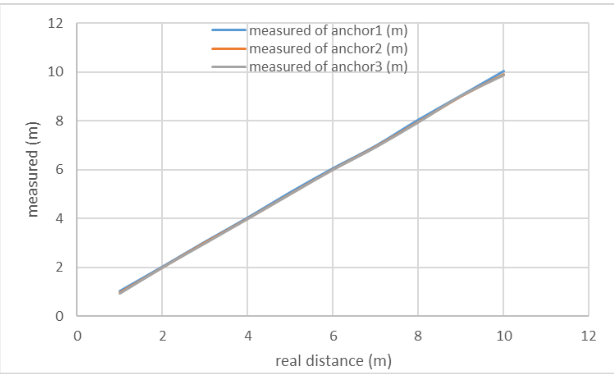

Fig. 4. Experimental evaluation of distance measurement.

Furthermore, an additional test was conducted by introducing a concrete barrier between two DWM1000 devices. Under this non-line-of-sight (NLoS) condition, the devices were unable to perform distance measurements, and no valid ranging data were obtained. These results indicate that the DWM1000 operates effectively only under line-of-sight (LoS) conditions.

Subsequently, experiments were conducted using the DWM1000 module to estimate the position of a mobile node based on the trilateration method. In the single-node scenario, the mobile node was positioned at several predefined locations within the workspace. At each location, approximately 30 measurement samples were collected. The resulting localization data are presented in Fig. 5.

The average total root-mean-square error (RMSE) was computed using the expression in Eq. (6), and the results are illustrated in Fig. 6. From the measurements conducted at six different positions, the RMSE and StD values are obtained as 10.08 cm and 3.09, respevtively. The average computation time required to estimate the position is 55 ms.

$$RMSE = \frac{1}{n}\sum_{i}^{n}\sqrt{(x_{ref} - x_i)^2 + (y_{ref} - y_i)^2} \quad (6)$$

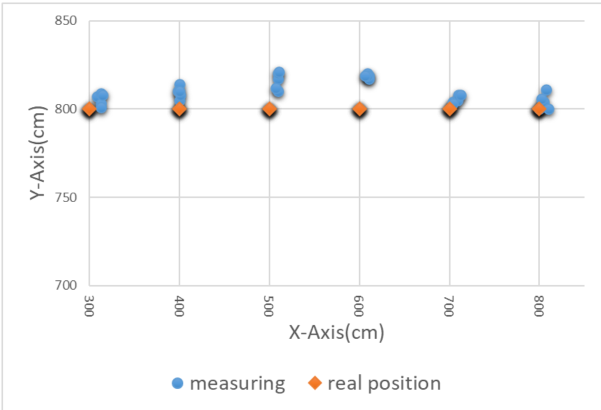

Fig. 5. Experimental results of one node position.

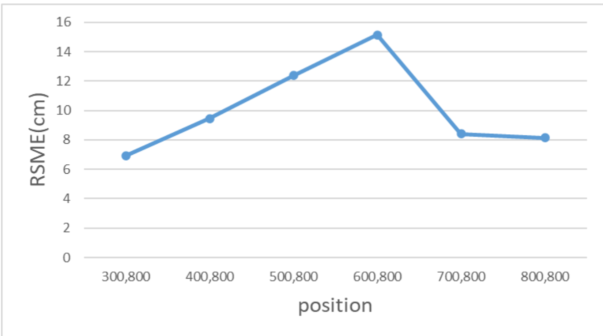

Fig. 6. Error position of single node.

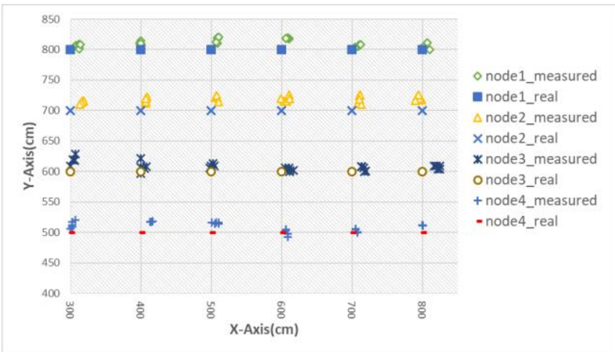

Fig. 7. Experimental results of four nodes position.

Further experiments were performed by increasing the number of mobile nodes to 2, 3, and 4 nodes. For each node position, 30 measurements were recorded, and the measured localization results along with the corresponding ground-truth positions are shown in Fig. 7.

The average measurement error profile for each node position is presented in Fig. 8. The obtained RMSE and StD values respectively are 11.46 cm and 2.61 for the second node, 12.25 cm and 3.68 for the third node, and 9.13 cm and 1.16 for the fourth node. These results indicate that the proposed localization system is capable of maintaining positioning accuracy at the centimeter level even when multiple nodes are simultaneously localized.

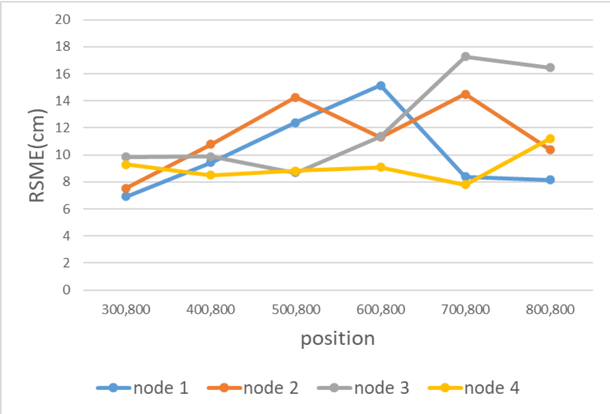

Fig. 8. RMSE Performance of the Multi-Node Localization System.

In terms of computational performance, the average time required for position estimation is 75 ms for two nodes, 95 ms for three nodes, and 115 ms for four nodes. The results show that the computation time increases approximately 20 ms for each additional node. This linear increase demonstrates that the proposed localization algorithm scales predictably with the number of mobile nodes, making it suitable for multi-node indoor localization applications such as robot swarm coordination.

IV. Conclusion

This study presented the development and experimental evaluation of a multi-mobile node localization system based on the UWB DWM1000 module and the trilateration algorithm. The proposed system utilizes three anchor nodes with known coordinates and employs the Symmetrical Double-Sided Two-Way Ranging (SDS-TWR) method to measure the distances between anchor nodes and mobile nodes. The experimental results demonstrate that the proposed system is capable of achieving centimeter-level localization accuracy within a 10×10 m workspace environment. For the single-node experiment, an average RMSE of 10.08 cm was obtained. When the number of mobile nodes increased to two, three, and four nodes, the localization accuracy remained relatively stable with RMSE values 11.46 cm, 12.25 cm, and 9.13 cm, respectively.

In addition, the experimental results show that the position estimation time increases linearly with the number of mobile nodes, with an average processing time of 55 ms for one node, 75 ms for two nodes, 95 ms for three nodes, and 115 ms for four nodes. This indicates that the computational overhead increases by approximately 20 ms for each additional node, demonstrating predictable scalability of the proposed localization framework. Overall, the results confirm that the proposed system provides a reliable and efficient solution for multi-node localization, making it suitable for applications such as robot swarm coordination, autonomous mobile robots, and real-time tracking systems. Future work will focus on improving localization robustness in complex indoor environments and integrating filtering techniques to further enhance positioning accuracy.

. Conflict of Interest

No Conflict of Interest. The authors declare that they have no conflict of interest regarding the publication of this paper.

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