HILS: A UWB-Based Hybrid Indoor Localization Scheme for Multi-Drone Environments

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***Abstract*—This paper presents a Hybrid Indoor Localization Scheme (HILS) for drones operating in indoor environments, utilizing Ultra-Wideband (UWB) technology to provision a high positioning accuracy to the drones. The proposed system combines Time Difference of Arrival (TDoA) for initial absolute position estimation and Two-Way Ranging (TWR) for precise relative distance measurements between a pair of drones. After computing their absolute positions via TDoA, the inter-drone distances derived from these positions are compared against TWR-measured distances. The discrepancies are iteratively reduced by particle filtering to enhance the positional accuracy of drones in indoor environments. This fusion approach leverages the complementary strengths of TDoA and TWR to reduce localization errors. Experimental results in simulation demonstrate that HILS significantly improves the localization accuracy of a scalable TDoA-based system.**

***Index Terms*—TDoA, TWR, Ultra-Wideband, particle filter, indoor localization**

I. Introduction

With the growing adoption of drones in commercial and industrial domains, their applications have expanded from outdoor surveillance to complex indoor missions such as inventory tracking, facility inspection, and multi-agent collaboration in global navigation satellite system (GNSS)-denied environments. These tasks require not only autonomy but also precise navigation capabilities. In indoor settings, where GPS signals are absent, traditional localization methods fall short in supporting real-time, accurate position tracking. As indoor drone operations increase in scale and complexity, the need for a dependable positioning system becomes paramount for ensuring both safety and mission success [1], [2].

Among various indoor localization technologies, including vision-based Simultaneous Localization and Mapping (SLAM), Wi-Fi fingerprinting, and Ultra-Wideband (UWB)-based positioning, UWB is notable for its high precision due to its robustness against multipath interference. Its two representative techniques, Time Difference of Arrival (TDoA) and Two-Way Ranging (TWR), offer a distinct trade-off [3]. TDoA provides excellent scalability with low communication overhead but requires precise anchor synchronization, as clock offsets can introduce significant positioning errors. Conversely, TWR delivers accurate ranging via bidirectional communication but incurs substantial overhead, which limits its scalability in multi-agent systems [4].

This paper aims at the problem of enhancing indoor multi-drone localization by developing a hybrid UWB-based positioning system. The system estimates initial drone positions using TDoA, and then refines those estimates by comparing inter-drone distances obtained via TWR. A particle filter minimizes the discrepancies between the two data types to iteratively improve positioning accuracy. The scenario is particularly relevant in cooperative drone missions where maintaining relative spatial awareness is essential for collision avoidance and task coordination. The proposed system is quantitatively evaluated in simulation-based experiments to assess its performance compared to the standalone implementations of TDoA and TWR [5], [6].

The main contributions of this paper are as follows.

- A Hybrid Indoor Localization Scheme (HILS) is developed by integrating Time Difference of Arrival (TDoA) for global positioning and Two-Way Ranging (TWR) for accurate inter-drone distance measurement.
- A particle filter is utilized to minimize discrepancies between TDoA-based position estimates and TWR-based distances, thereby enhancing the localization accuracy of the scalable TDoA approach.
- The results show a significant localization accuracy improvement over the highly scalable TDoA approach, while demonstrating a practical trade-off compared to the high-overhead TWR approach.

II. Related Work

Improving the localization accuracy of UWB-based systems has been explored through various approaches such as hardware calibration, filtering techniques, sensor fusion, and algorithmic refinement.

Accurate hardware calibration significantly affects system reliability. [7] developed a second-order compensation algorithm that leverages inter-anchor distance constraints to refine positioning accuracy. Their method yielded a root mean square error (RMSE) of approximately 6cm, demonstrating consistent improvements in anchor-based localization even in the absence of external calibration references.

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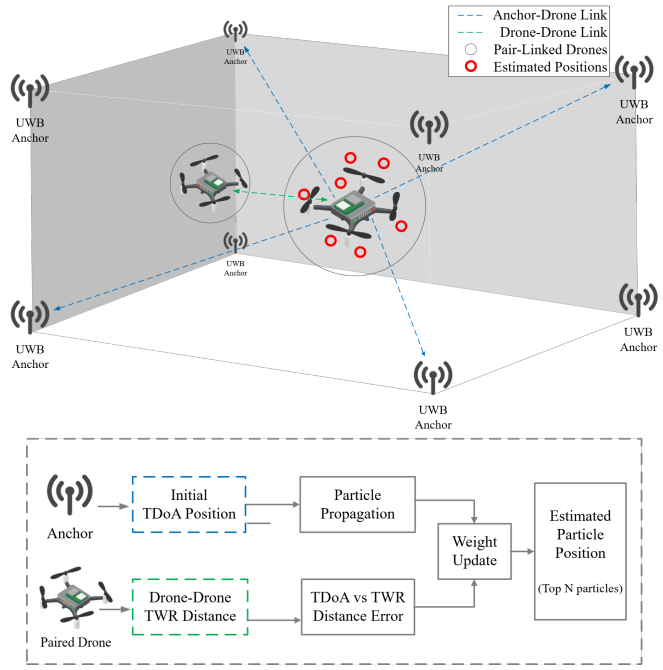

Fig. 1. Overview of the Proposed Hybrid Indoor Localization Scheme (HILS)

Advanced filtering methods, particularly integrating multiple sensing modalities, have enhanced robustness in complex environments. [8] proposed a fusion of UWB with LiDAR-SLAM using Factor Graph Optimization (FGO), coupled with a grey prediction model for correcting NLoS-induced errors. Their approach achieved a planar localization accuracy of 8.6 cm and remained effective under challenging geometric anchor configurations.

Multi-sensor fusion has also emerged as a reliable strategy for comprehensive spatial awareness. [9] combined UWB ranging with dual barometric sensors to support high-resolution 3D localization. The use of Kalman filtering enabled the system to reach a height accuracy of ± 0.05 m and an overall 3D RMSE of 0.074 m.

Other research has focused on eliminating the need for anchor synchronization while maintaining both high accuracy and scalability. [10] developed a Virtual Two-Way Ranging (V-TWR) scheme that allows an unlimited number of tags to achieve localization by passively overhearing anchor-to-anchor message exchanges. This method effectively removes the synchronization requirement typical of TDOA systems and avoids the collision issues of TWR systems, reporting a median accuracy of 10.5 cm.

III. Proposed Method

To achieve a practical balance between localization accuracy and system scalability for multi-drone operations, we propose a Hybrid Indoor Localization Scheme (HILS). This scheme integrates Time Difference of Arrival (TDoA) for scalable absolute positioning with Two-Way Ranging (TWR) for resource-efficient, high-precision relative distance correction. An overview of this architecture is presented in Fig. 1, which illustrates the virtual layout of the system and the algorithmic data flow. The core of HILS is a cooperative, two-stage particle filter framework that synergistically fuses data from both methods of TDoA and TWR. The key innovation lies in its sequential, cooperative particle weighting process, which efficiently leverages both TDoA and TWR measurements. The process is executed in two main stages for each drone k.

A. Stage 1: Candidate Selection via TDoA Likelihood

First, a primary likelihood assessment is performed for all particles of drone k using the global TDoA measurements from the fixed anchors. For each particle $\mathbf{p}_k$, its consistency with the measured TDoA data is evaluated. The expected TDoA value for a particle's position between a pair of anchors (an anchor j and a reference anchor r) is calculated as:

$$\hat{\tau}_{kj}(\mathbf{p}_k) = \frac{\|\mathbf{p}_k - \mathbf{a}_j\| - \|\mathbf{p}_k - \mathbf{a}_\mathrm{r}\|}{c}, \tag{1}$$

where $\mathbf{a}_j$ and $\mathbf{a}_\mathrm{r}$ are the positions of the anchors and c is the speed of light.

The TDoA-based likelihood, $L_{\mathrm{TDoA}}(\mathbf{p}_k)$, is then determined by comparing these expected values with the actual measured TDoA values, $\tau_{kj}^{\mathrm{meas}}$, under a Gaussian noise model:

$$L_{\mathrm{TDoA}}(\mathbf{p}_k) \propto \exp\left(-\frac{1}{2}\sum_{j\neq \mathrm{r}} \frac{(\hat{\tau}_{kj}(\mathbf{p}_k) - \tau_{kj}^{\mathrm{meas}})^2}{\sigma^2_{\mathrm{TDoA_time}}}\right), \tag{2}$$

where $\sigma_{\mathrm{TDoA_time}}$ is the standard deviation of the TDoA measurement noise.

Based on these likelihood scores, a candidate set of the most promising particles (denoted as S_k^*) , is formed by selecting the top 10% of particles. This initial step effectively filters out improbable position hypotheses and focuses computational resources on a high-probability region.

B. Stage 2: Weight Refinement via Inter-Drone TWR

Subsequently, a second weighting step is performed exclusively for the particles within the candidate set S_k^*, using the precise inter-drone TWR measurements. A crucial aspect of this stage is the use of a dynamically refined reference position for the paired drone j. Instead of using a potentially stale past estimate, its reference position, $\mathbf{p}_j^*$, is actively calculated as the centroid of its own set of top 10% TDoA-ranked particles, S_j^*:

$$\mathbf{p}_j^* = \frac{1}{|S_j^*|}\sum_{\mathbf{p}\in S_j^*} \mathbf{p}. \tag{3}$$

This provides the most current and probable peer location for the TWR evaluation. The TWR likelihood for a candidate particle $\mathbf{p}_k \in S_k^*$ is then calculated using this refined peer position:

$$L_{\mathrm{TWR_drone}}(\mathbf{p}_k, \mathbf{p}_j^*) \propto \exp\left(-\frac{1}{2}\cdot\frac{(\|\mathbf{p}_k - \mathbf{p}_j^*\| - d_{kj}^{\mathrm{TWR}})^2}{\sigma^2_{\mathrm{TWR_drone}}}\right), \tag{4}$$

where d_{kj}^{TWR} is the measured distance between drones k and j, and $\sigma_{\mathrm{TWR_drone}}$ is the standard deviation of the TWR inter-drone measurement noise.

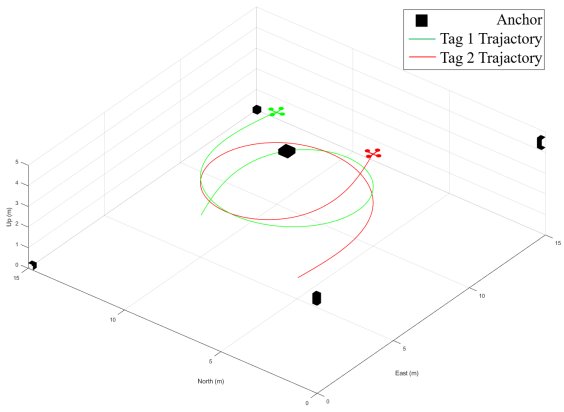

Fig. 2. Simulated 3D Trajectories for the Two UAVs in the LoS Environment

Finally, the definitive weight w_k for each particle of drone k is determined. Particles in the candidate set S_k^* have their weights refined by multiplying their TDoA likelihood by the TWR likelihood. All other particles outside this set are discarded by receiving a weight of zero:

$$w_k = \begin{cases} L_{\text{TDoA}}(\mathbf{p}_k) \cdot \prod_{j \neq k, \text{paired}} L_{\text{TWR_drone}}(\mathbf{p}_k, \mathbf{p}_j^*) & \text{if } \mathbf{p}_k \in S_k^*, \\ 0 & \text{if } \mathbf{p}_k \notin S_k^*. \end{cases} \tag{5}$$

This cooperative and sequential weighting strategy tightly couples the estimation processes of the drones, leveraging the most reliable TDoA information to refine TWR-based corrections. This approach enhances accuracy while focusing computational resources on the most promising particles. This architecture's efficiency is also evident in terms of its communication overhead. While a conventional TDoA system requires only a single message per update and a Double-Sided Two-Way Ranging (DS-TWR) system with four anchors needs approximately 12 messages, HILS strikes a practical balance by using only four messages—one 'blink' for TDoA and a three-message TWR exchange with a single paired drone. After the weighting step, a resampling process is performed if needed, and the final position is computed from the highest-scoring particles.

IV. Performance Evaluation

This section details the simulation environment and presents a comparative performance analysis of the proposed HILS against standalone TDoA and TWR localization schemes.

A. Experimental Setup

The simulation environment and all localization schemes were implemented in MATLAB, utilizing the UAV Toolbox for drone dynamics and trajectory modeling, and the Communications Toolbox for simulating UWB signal propagation [11]. The simulation was conducted in a $15 \times 15 \times 5$ meter indoor environment, representative of industrial space. The UWB transceivers used in this system operate in compliance with the IEEE 802.15.4z standard [12], transmitting at a center frequency of 6.5 GHz in High Pulse Repetition Frequency (HPRF) mode. Five UWB anchors were deployed at the corners and ceiling center of the space to ensure robust 3D coverage. To evaluate the system's performance in multi-tag scenarios, two drones were deployed along pre-defined 3D trajectories with distinct altitude bands. Each drone followed a grid-like path consisting of waypoints, covering the full area in 500 time steps. These flight trajectories were designed to reflect realistic inspection or mapping patterns and are visualized in Fig. 2.

This anchor configuration introduces signal propagation delays that vary based on the relative positions of drones and anchors. For TDoA measurements, the propagation delay between an anchor i and a drone j is calculated as $\tau_{ij} = \frac{d_{ij}}{c}$, where d_{ij} represents the Euclidean distance between them and c is the speed of light. While real-world indoor environments introduce further complexities such as multipath propagation, this study focuses on a Line-of-Sight (LoS) scenario to establish a foundational performance baseline. To incorporate a degree of realism into this baseline, key measurement errors were modeled. Specifically, a synchronization error reflecting minor clock drift was introduced for TDoA, where the arrival time of each signal was perturbed by a random error drawn from a Gaussian distribution with a standard deviation of 1 ns, and the standard deviation for TWR-based ranging estimates in the filter's measurement model was set to 0.03m.

B. TDoA-Only Baseline

The TDoA-only baseline is implemented to serve as a direct performance comparison against our hybrid approach. In this configuration, a drone's position is estimated using only TDoA measurements received from the fixed anchors.

Within the particle filter framework, the weight of each particle is updated based solely on the TDoA likelihood function, as defined in (2). The process for calculating the expected TDoA value $\hat{\tau}_{ij}(p_i)$ for each particle also follows the model described in (1). This baseline isolates the performance of the traditional TDoA approach within our simulation environment, serving as a benchmark for scalability.

C. TWR-Only Baseline

The TWR-only baseline serves as a benchmark for high-precision localization. In this approach, a drone's position is estimated using direct distance measurements to each of the fixed anchors, obtained via DS-TWR [6]. The particle filter's weights are updated using a likelihood function that evaluates the consistency between the measured anchor distances and the calculated distances from each particle's position to the anchors. While highly accurate, this method's scalability is limited by its high communication overhead.

D. Testing Results

Each experimental scenario was repeated 50 times using the predefined drone trajectories to ensure statistical reliability. The performance of HILS was compared against standalone TDoA and TWR methods in terms of localization accuracy, measured by RMSE and statistical error metrics.

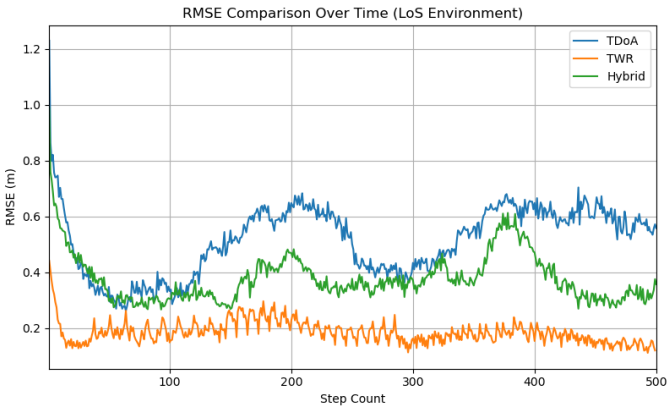

Fig. 3. RMSE Comparison Over Time in LoS Environment

TABLE I
LOCALIZATION ERROR STATISTICS IN LOS ENVIRONMENT

Method	Mean (m)	Max (m)	Min (m)	Std Dev (m)
TDoA	0.469	1.590	0.051	0.236
TWR	0.178	0.528	0.069	0.054
HILS	0.345	1.285	0.029	0.167

Fig. 3 and Table I present the results in the LoS environment. The TWR-only baseline achieved the highest accuracy with a mean RMSE of 0.178 m, establishing the 'gold standard' for precision. However, its requirement for bidirectional communication with multiple anchors makes it impractical for large-scale drone deployments due to high network overhead. At the other end of the spectrum, the TDoA-only baseline offers excellent scalability but showed the highest mean error of 0.469 m.

Our proposed HILS method has successfully addressed this trade-off. By using inter-drone TWR to correct the TDoA estimates, HILS reduced the mean localization error to 0.345 m, which is a 26.4% improvement over the TDoA baseline. This demonstrates that HILS provides a substantial accuracy enhancement while preserving the fundamental scalability of TDoA, offering a practical and effective solution for multi-drone systems.

V. CONCLUSION

This paper proposed a hybrid indoor localization scheme (HILS) that enhances the accuracy of a scalable TDoA system by incorporating precise, peer-to-peer TWR measurements within a particle filter framework. Simulation-based evaluations demonstrate that HILS reduces the average localization error by 26.4% compared to a standalone TDoA system in LoS environments. While a TWR-only system provides higher accuracy in LoS, it is unsuitable for scalable deployments due to its high communication overhead. HILS effectively leverages the complementary strengths of both techniques, establishing a robust and practical solution that balances the critical demands of localization accuracy and system scalability for multi-drone operations. As future work, we will explore adaptive inter-drone ranging strategies and advanced filtering techniques. We will also pursue real-world deployment to validate our system's performance, particularly in challenging Non-Line-of-Sight (NLOS) environments.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2023R1A2C2002990), and also by the Institute of Information & Communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (No. RS-2024-00398199). Note that Jaehoon (Paul) Jeong is the corresponding author.

REFERENCES

[1] F. Zafari, A. Gkelias, and K. K. Leung, "A survey of indoor localization systems and technologies," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 3, pp. 2568–2599, 2019.

[2] J. Tiemann, F. Schweikowski, and C. Wietfeld, "Design of an uwb indoor-positioning system for uav navigation in gnss-denied environments," in *2015 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*. IEEE, 2016, pp. 1–7.

[3] A. Alarifi, A. Al-Salman, M. Alsaleh, A. Alnafessah, S. Al-Hadhrami, M. A. Al-Ammar, and H. S. Al-Khalifa, "Ultra wideband indoor positioning technologies: Analysis and recent advances," *Sensors*, vol. 16, no. 5, p. 707, 2016.

[4] J. Tiemann, F. Eckermann, and C. Wietfeld, "Atlas - an open-source tdoa-based ultra-wideband localization system," in *2016 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, 2016, pp. 1–6.

[5] Z. Shi, H. Li, H. Lin, and L. Huang, "A nano-quadcopter formation flight system based on uwb indoor positioning technology," in *2018 13th International Conference on Computer Science Education (ICCSE)*, 2018, pp. 1–4.

[6] M. Strohmeier, T. Walter, J. Rothe, and S. Montenegro, "Ultra-wideband based pose estimation for small unmanned aerial vehicles," *IEEE Access*, vol. 6, pp. 57 526–57 535, 2018.

[7] M. Qi, B. Xue, and W. Wang, "Calibration and compensation of anchor positions for uwb indoor localization," *IEEE Sensors Journal*, vol. 24, no. 1, pp. 689–699, 2024.

[8] Z. Chen, A. Xu, X. Sui, Y. Hao, C. Zhang, and Z. Shi, "Nlos identification- and correction-focused fusion of uwb and lidar-slam based on factor graph optimization," *Remote Sensing*, vol. 14, no. 17, p. 4258, 2022.

[9] L. Bao, K. Li, J. Lee, W. Dong, W. Li, K. Shin, and W. Kim, "An enhanced indoor three-dimensional localization system with sensor fusion based on ultra-wideband ranging and dual barometer altimetry," *Sensors*, vol. 24, no. 11, p. 3341, 2024.

[10] J. Yang, B. Dong, and J. Wang, "Vuloc: Accurate uwb localization for countless targets without synchronization," *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, vol. 6, no. 3, Sep. 2022.

[11] T. M. Inc., "Matlab version: (r2025a)," Natick, Massachusetts, United States, 2025. [Online]. Available: https://www.mathworks.com

[12] The MathWorks Inc., "Uwb ranging using IEEE 802.15.4z," 2025. [Online]. Available: https://kr.mathworks.com/help/comm/ug/uwb-ranging-using-ieee-802.15.4z.html