Proceedings of CONF-CDS 2026 Symposium: Machine Learning and Neural Network Applications in Engineering
DOI: 10.54254/2755-2721/2026.AST35556

Time Difference of Arrival Localization Based on Ultra-Wideband: A Synergistic Method of System and Algorithm

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Abstract. The UWB is a short-range wireless communication technology using very wide bandwidth RF pulses. UWB communication could provide a high-level accuracy for autonomous tracking and localization. However, the UWB ranging based on the Time Difference of Arrival method (TDoA) would often be compromised by non-ideal environmental conditions, antenna propagation delays and multiple path effects, etc. This paper introduces a method to optimize a UWB localization system based on DW1000, combined with the hardware features of modules and algorithmic approaches. Systematically, it addresses the hardware limitations by simulating and comparing antenna designs and implementing the antenna-delay calibration, maintaining the pulse signal integrity. Also, this study establishes a rigorous TDoA mathematical model to demonstrate three mainstream localization algorithms: Fang, Chan and Taylor through comprehensive Monte Carlo simulations. The evaluations considered different anchor densities, from 3 to 7, with the addition of white Gaussian noise (AWGN) levels and distinct operational boundaries based on macroscopic channel models. The testing result demonstrates that Chan's algorithm achieved the lowest simulated error under AWGN among the tested algorithms, but Taylor's expansion represents a superior robustness in non-Gaussian environments with multipath fading. In conclusion, the hardware experiments verified UWB TWR ranging and two-anchor geometric positioning. TDoA localization algorithms were then studied through MATLAB simulation as a potential extension for multi-anchor localization. Thereby, a hybrid method is required, combined with hardware strategies and software algorithms. The software utilizes the TDoA localization with Taylor-series iterative refinement.

Keywords: Time Difference of Arrival (TDoA), Ultra-Wideband (UWB), Chan's algorithm, Fang's algorithm, Taylor's algorithm

1. Introduction

The rapid development of autonomous robotic platforms, like industrial vehicle trolleys, or auto-following robots, they heavily rely on high accuracy and real-time tracking systems. The Ultra-Wideband (UWB) technique [1] is a unique and outstanding choice for short-range positioning, with an operating frequency range 3.1GHz to 10.6GHz with more than 500MHz bandwidth. UWB uses a short pulse to transmit data instead of continuous waves. In this case, UWB can offer better

DOI: 10.54254/2755-2721/2026.AST35556

multipath resolution and some obstacle tolerance compared with narrowband systems, but non-line-of-sight conditions and conductive/concrete barriers still significantly degrade performance.

Although UWB hardware has inherent high precision, the ranging result of raw measurement will still be subjected to many aspects, such as propagation delay or calibration errors. Also, using standard time of arrival techniques requires absolute synchronization between transmitters and receivers. In real-world circumstances, this requirement is unfeasible with dynamic applications. Hence, to avoid the constraint of real-world problems, the Time Of arrival Difference [2] (TDoA) method is deployed. TDoA reduces the need for synchronization between the tag and the anchors, but practical TDoA systems still require synchronized anchors or compensation for inter-anchor clock offsets.

However, the raw measurement from TDoA is not robust enough to make precise localizations in the real application environment due to various types of noise, like white Gaussian noise, which leads to complex and non-linear mathematical functions. Thereby, a framework consisting of a synergistic approach combined with a UWB hardware system with advanced computerized algorithms and is necessary. Multiple algorithms like Fang's, Chan's and Taylor's [3] are applied to linearize the complex system and increase the processing efficiency and mitigate additive environmental noise. In the system, UWB provides reliable measurement data and algorithms act as an iterative filter to provide precise and convergent positional tracking.

This paper discusses the integration of physical UWB systems and its corresponding TDoA algorithms. It will focus on hardware-ranging methodologies along with mathematical optimization and how combining the physical position of UWB with the computationally enhanced TDoA algorithms establishes a highly effective method for auto-following and localization systems.

2. Hardware of UWB & algorithms

The UWB system evaluated in this work is a physical implementation. The evaluated module was the Makerfabs ESP32-UWB, integrating an ESP32 controller with a BU01/DWM1000-based UWB module. Arduino libraries were used for programming and testing. Understanding the internal block dynamics of these hardware entities is essential for quantifying the error propagation pathways that degrade TDoA calculations.

2.1. The UWB module

In this research, the core RF operation is achieved by DW1000 transceivers, which satisfy the IEEE 802.15.4-2011 [4] UWB standard. This component uses an Impulse radio UWB (IR-UWB) architecture and produces coherent pulses across channels 1 to 5 with a central frequency from 3.5 GHz to 6.5 GHz. The bandwidth allocation is 499.2MHz. This chip is run by ESP32. With a DW1000 library and an ESP32 simulation library based on the Arduino, we achieved using Arduino microcontroller to manipulate the process of the DW1000 chip and also the UWB module the chip is based on. Hence, in hardware architectures, this system is capable of making two-way ranging, with an error range of 10cm and a 6.8M bps data transmission speed.

For DW1000, when the UWB pulse reaches the receiver antenna, the RF processor will down--convert and digitize the signal. The digital signal will then be executed by a high-speed correction mechanism by the core processor and sampled into a Channel Impulse Response (CIR) [5] accumulator. The accumulator will use an internal clock to generate a sampling frequency of 64GHzm, which means a timing resolution of around 15.6 picoseconds/sample.

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To calculate the arrival time, the DW1000 will run a Leading Edge Detection (LDE) [6] algorithms, based on the accumulated CIR, not simple peak detection, which is extremely weak after multipath reflections arriving after a primary signal. The LDE function block can figure out the noise floor and establish a signal threshold. When the CIR crossed the first point of threshold value, it was taken as the first path index and defined the raw arrival timestamp.

In this case, any hardware degeneration will cause the LDE shifting the threshold point and inputting some jitter into the tracking loop based on TDoA.

2.2. The real-time positioning & ranging methods

The ranging process inside a UWB system network will fundamentally rely on the Two-Way Ranging (TWR) protocol that devices exchange continuous signal pulses to determine the distance between them. Different methods are designed based on this mechanism to improve its quality.

2.2.1. Single-sided two-way ranging

In the basic signal-sided two-way ranging method [7], the ranging calculation is based on a simple request-and-response message exchange between two devices. As Figure 1 illustrates, the initiator device sends a message to a receiver. The receiver then subsequently replies to a message back to the initiator and completes a cycle. The signal's time of flight [5] (ToF) is physically worked out by half of the difference between the total duration time and the reply time in processing, giving the absolute distance between the tag and the anchor. Apparently, there's a critical vulnerability that exists in measurement. More specifically, the ranging error scales linearly in relation to the duration of the reply time. Therefore, if the internal clock in one anchor and the tag of it are not fully synchronized, the calculations this system makes will be inaccurate. Due to this linear accumulation of synchronization errors over time, this single-sided method is strictly suitable only for short-range localization applications.

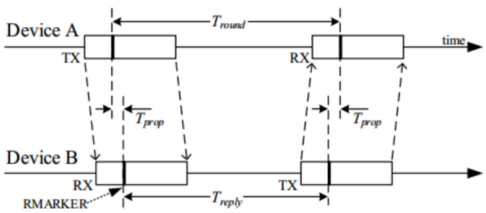

Figure 1. Structure of single-side ToF ranging data [8]

2.2.2. Double-sided two-way ranging

To improve the synchronization problem existing in the single-sided approach, Double-sided Two-way Ranging (DS-TWR) made some fundamental modifications by adding an extra feedback message exchange between the tracking devices to significantly diminish measurement errors. As Figure 2 details, this approach can be implemented by a three-message or a four-message protocol.

In the three-message approach, three sequential signals are exchanged between devices, allowing the system to work out six distinct timestamps that are eventually processed to yield a highly accurate Time of Flight (ToF) [6] calculation. Although this double-sided method effectively reduces the time drift, it requires that the forward and backward propagation delays are absolutely symmetrical. To achieve outstanding accuracy, we use a four-message mode to account for

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asymmetrical propagation routes. However, more power is needed to capture this extra message and produce a higher latency overhead inside the tracking loop. In this case, the three-message with a DS-TWR mode was purposefully chosen instead of the four-message method. In general, a lower system processing delay produces a greater net benefit to the localization framework compared to maximizing individual hardware precision. Since the target vehicle is equipped with a number of tags, any minor localized distance errors are mathematically eliminated during subsequent angular processing.

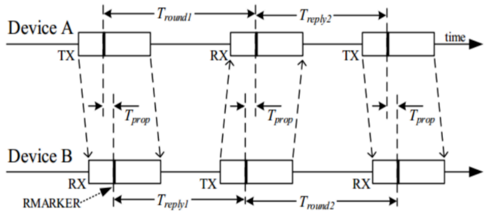

Figure 2. Structure of two sides ToF ranging data [8]

2.2.3. Time of Arival (ToA)

In the system of real-time localization, the Time of Arrival (ToA) technique calculates the specific distance by measuring the exact time delay between signals arriving from one target to another or more base stations that are set. As shown in Figure 3 shown about, the basic principle depends on translating those flight times from place to place into a physical distance figure. However, this methods' partibility heavily depends on the nature of the transmission medium and the accuracy of the system time accounting abilities. When using electromagnetic waves, the system requires a precise and synchronized clock to precisely capture the minute delays. In order to minimize the high-level hardware requirements, some extra configurations may be introduced into the system to make a reference signal. In this study, an extra HC-12 microwave commute module is added to the system to act as a dependence timing mechanism.

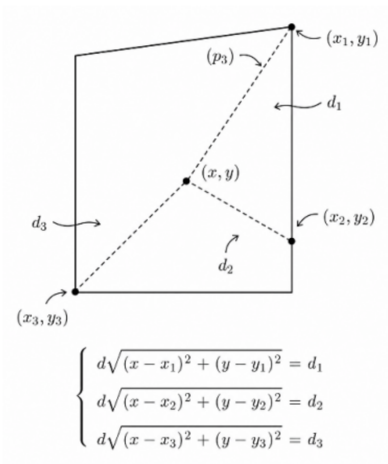

Figure 3. Structure of the Time of Arrival method

2.2.4. Time of Difference of Arrival (TDoA)

To break through the strict hardware synchronization that constrains the method of standard ToA systems. The Time Difference of Arrival (TDoA) method [9] offers a highly robust alternative choice for real-time localization. As mentioned before, achieving full clock synchronization between independent transmitters and recievers face a huge challenge, making the method practically impossible using high-speed electromagnetic waves. TDoA is a method that deliberately detours this requirement. Instead of computing absolute transit times, this differential method utilizes the individual arrival times at different base stations and subtracts them to work out the time variance. For example, if four individual base stations were used, the localization system could generate three distinct TDoA measurements from point to point by time difference. AsFigure 4 represents, the relative time difference is subtracted from the intersection curves, which accurately resolve the target's physical position, without a fully synchronized system needs to maintain a perfect clock between anchors, which is the reason this method is chosen to be applied in this system.

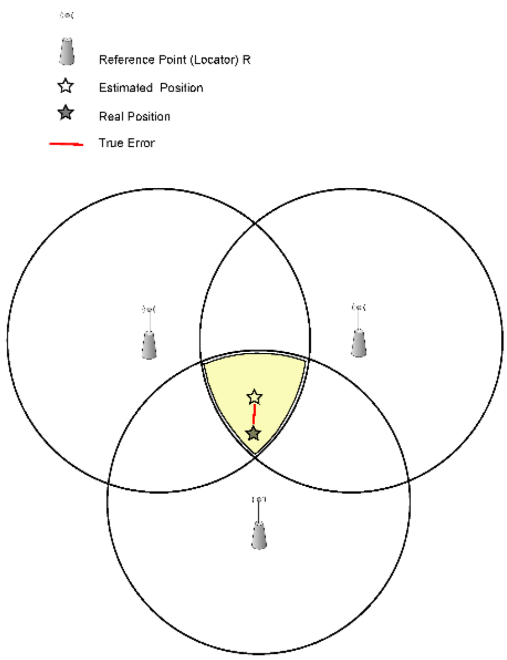

Figure 4. TDoA with three anchors architecture [10]

2.3. Algorithms to achieve TDoA

Based on the time of flight from all anchors set for the system, various kinds of methods can be used to achieve the TDoA localization. There are numbers of algorithms to compute TDoA and the accuracy of TDoA results could improve depending on the different algorithms. Using these algorithms, the testing platform could overcome the noise that exists in the hardware LDE function and improve the non-linearity, computation efficiency and convergence.

2.3.1. Fang's algorithm

Fang's algorithm provides an accurate, closed-form algebraic solution for TDoA localization using linearized hyperbolic equations into a single-variable quadratic equation. In order to reduce the complexity of the process, this algorithm constructs a constrained coordinate system, setting two base stations as the reference base stations allocated on the same horizontal axis (y=0). Working out the solution of the quadratic function based on this coordinate series, the target coordinates can be directly worked out throughout the equation. However, there's a limitation that exists in Fang's algorithm with its structural extensivity; due to Fang's algorithm, it can operate with only three base

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stations (M=3), making it unsuitable for more complex, redundant localization networks. The theory of Fang's algorithm can be checked in [11].

2.3.2. Chan's algorithm

Chan's algorithm is a highly efficient and non-iterative method for TDoA localization, especially for situations equipped with more than three base stations. The Chan's method is based on a statistical assumption: the TDoA measurement errors of a Gaussian random variable are assumed to be zero. To work out the non-linear hyperbolic equations, Chan's algorithms use a two-stage least-squares technique. Firstly, it sets an intermediate variable to linearize the system temporarily and work out a position estimation. Then, using a second least-squares function to optimize the solution by eliminating the squared error terms. This process reduces the load of processes and effective dimmish the noise in redundant networks without producing convergence failures, which are common in iterative methods. More details can be found in *A simple and efficient estimator for hyperbolic location* [12].

2.3.3. Taylor's algorithm

The most classical algorithm with a high robustness. This method requires an initial estimation for the target's precise location to start its calculations. This starting point might be generated by a primary method like Chan's method to ensure a steady convergence. From the initial value, the Taylor method establishes a linearized model and repeatedly applies least-squares adjustments to iterate the coordinate values. The recursive matrix optimization runs in a loop (Δx and Δy) until convergent to an extremely small value. However, although Taylor expansion could achieve a high accuracy with significant noise, the computational efficiency and the ability to converge still largely depend on the accuracy of the initial position estimation.

3. Hardware testing & simulation

3.1. Verification of UWB hardware system

To evaluate the performance of the UWB hardware system, the platform used two ESP32-UWB modules with DW1000 chips to make a test in a basic ranging configuration. One module is set as an anchor and the other was set as a tag.

However, it is clear that offsets exist in the system due to many sources. Generally, the main source of offsets comes from antenna delay inside the DW1000 module. From the datasheet of the module, the signal propagation time includes the actual time of flight, the transmission time and the reception antenna delays. The total measurement time can be expressed as:

$$t_{Measured}=t_{ADTX}+TOF+t_{ADRX} \quad (1)$$

$t_{Measured}$ is the total measurement time, t_{ADTX} is the transmitter delay, t_{ADRX} is the receiver delay and TOF is the actual time of flight.

To constrain this delay, a calibration function was used. Two modules were placed at a fixed distance of 1 m, as shown in Figure 5. Then, the program lunched a delay offset that was swept from 100 ns to 10000 ns with 100 ns steps. For each offset value, the measurement was compared with the known 1 m reference distance. The offset that produced the closest result was selected as the antenna delay compensation value.

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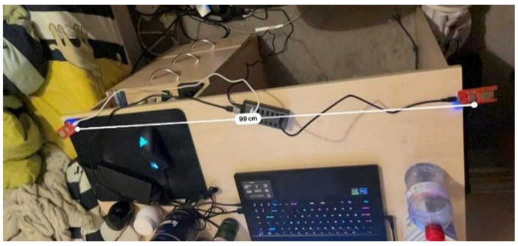

Figure 5. Offset measure in short range

After the calibrated delay offset was added to the anchor code, the ranging accuracy improved significantly, as shown in Figures 6 and 7.

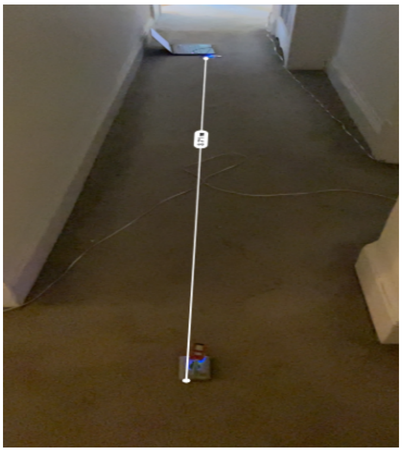

Figure 6. Offset measure in 3.7m

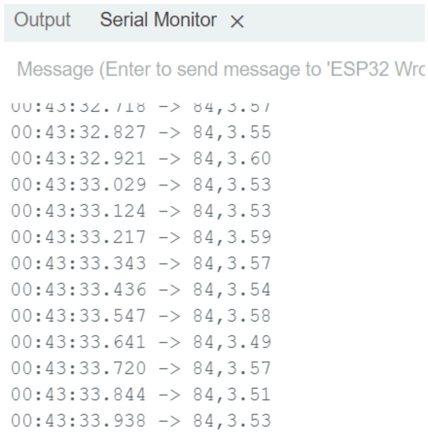

Figure 7. Measurement in concel

Since checking the ranging accuracy of single-anchor system, two-anchor method is introduced into testing. It was conducted to estimate the distance and angular direction of the tag. In this test, two anchors were fixed into a known distinctive place with distance c, the the tag was treated as a mobile object. The modules measured the distance of a and b from the tag of two anchors, using the cosine rule test to calculate the range-based geometric positioning.

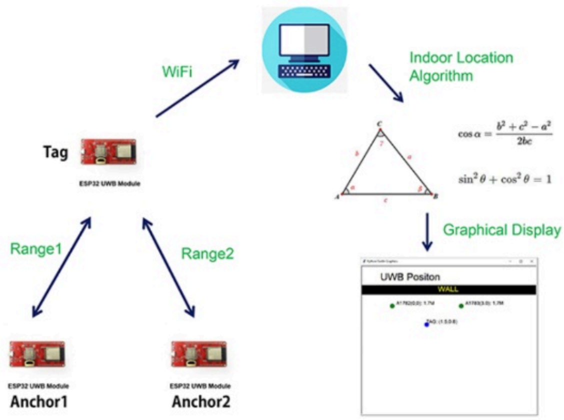

Figure 8. The process of anchors positioning [13]

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The experiment result is shown in Figures 9 and 10. As the tag moving, the calculated position changes correspond to match the actual standing position of the user approximately.

Figure 9. Positioning test using two anchors

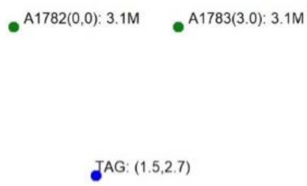

Figure 10. Positioning test with tag was moved further away

3.2. The equation of TDoA system

Since the TOF information is obtained from anchors, the TDoA method can be implemented for localization. Without any noise, this system can directly implement geometry between targets and anchors to figure out the location of the target. However, in the real world, the practical UWB system has measurements of arrival time with additive noise, antenna delay, etc. Thereby, algorithmic processing is needed to improve the accuracy, efficiency and stability of convergence of the system.

Hence, if there are M number of base stations equipped with a trolley vehicle or the controller, the position of the i-th base station can be expressed as

$$s_i=(x_i,y_i) \tag{2}$$

With an unknown target is

$$u=(x,y) \tag{3}$$

The signal received at the i-th station can be represented as a delay version of the transmitted signal with noise in addition. The delay at each base station can be determined by the propagation distance from the target to the base station.

Taking the first base station as the reference, the TDoA measurement between the i-th base station and the first base station can be written as

$$t_{i1}=t_i-t_1 \tag{4}$$

With the distance between stations is

$$d_{i1}=d_i-d_1=ct_{i1} \tag{5}$$

Here, c is the light speed, di is the distance between target and i-th base station and d_1 is the distance between target and reference station. Therefore, the distance between target and the i-th base station is

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$$d_i=\sqrt{\left(x-x_i\right)^2+\left(y-y_i\right)^2} \tag{6}$$

Hence, the TDoA localization method can be represented as the hyperbolic equation here

$$ct_{i1}=\sqrt{\left(x-x_i\right)^2+\left(y-y_i\right)^2}-\sqrt{\left(x-x_1\right)^2+\left(y-y_1\right)^2} \tag{7}$$

To solve this nonlinear equation to provide an estimated target position, the later simulation tested three TDoA localization algorithms, which are mentioned: Fang's algorithm, Chan's algorithm, and Taylor's algorithm.

3.3. The simulation of Fang, Chan, and Taylor algorithms

To evaluate the performance of these algorithms, MATLAB simulations were performed under additive white Gaussian noise. The number of anchors varied from 3 to 7, and the localization performance of each algorithm was compared.

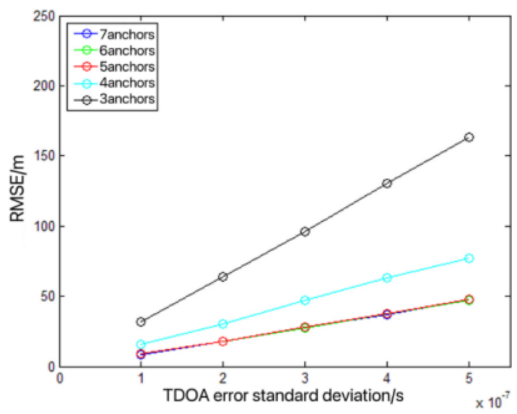

Figure 11. Simulation with Chan's method

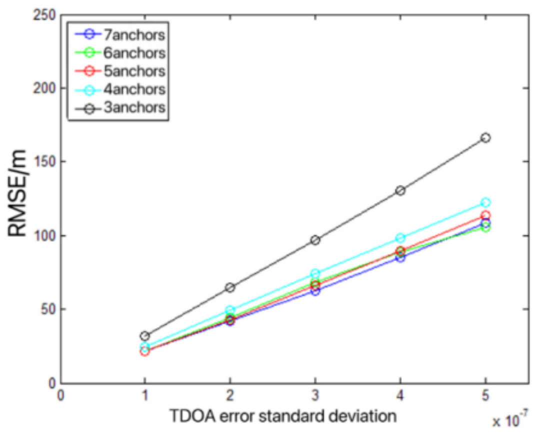

Figure 12. Simulation with Taylor's method

Figures 11 and 12 are the simulation results of Chan's and Taylor's algorithms with AWGN added. It can be seen that the Chan's method benefits from an increased number of anchors. When the number of anchors in simulation increases, the precision and stability of redundant TDoA measurements improve in the level of least-square estimation. However, when the number of anchors is more than 5, the improvement from adding anchors is less significant. This shows adding more anchors than a certain level will provide a limited number of benefits.

To further approximate a real propagation environment, repeat the simulation for different anchor numbers with a number of anchors from 4 to 7, and the simulation will be performed within a channel model environment of the COST259 model [14] to give a clear standard. The TDoA error in standard deviation was fixed at 0.1us with the radius of the model starting from 1000m to 5000m. This simulation will evaluate a comparative algorithm stress test of three algorithms in a more complex and non-AWGN environment.

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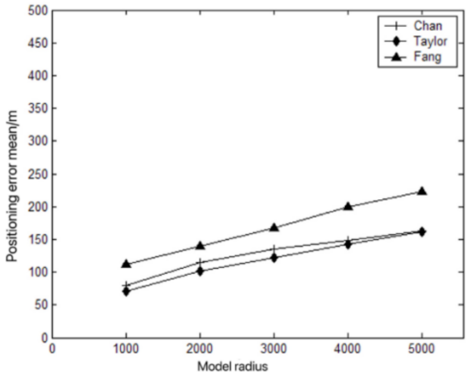

Figure 13. Simulation with 4 anchors

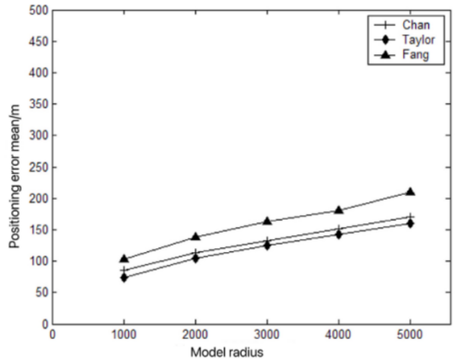

Figure 14. Simulation with 5 anchors

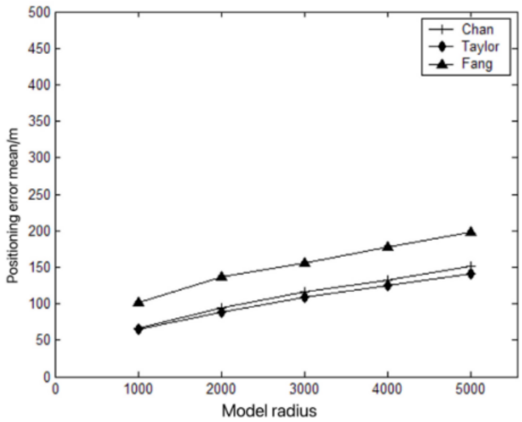

Figure 15. Simulation with 6 anchors

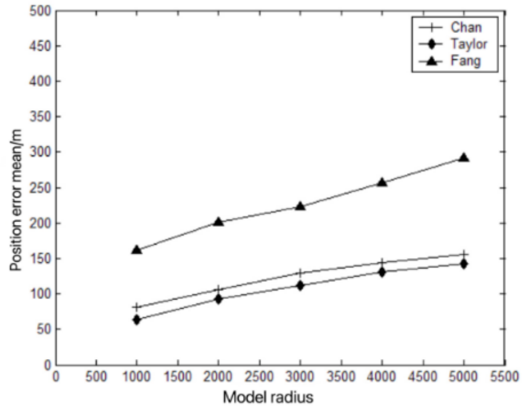

Figure 16. Simulation with 7 anchors

Unlike the case in AWGN, the simulations under COST259 show that both Chan's and Taylor's algorithms performed better compared to Fang's algorithm. Additionally, Taylor's algorithm shows a stronger robustness compared to the other two algorithms with different anchor configurations.

From these simulation results, when the environment represents non-Gaussian under the multipath propagation and channel fading, like the model of COST259, the performance of Chan's algorithm decreases. Conversely, Taylor's algorithm can iteratively converge the position estimation and show better robustness, provided that a suitable initial estimate is available.

In general, the Chan's algorithm is attractive based on the point of computational efficiency to provide a closed solution even under a noisy environment. Fang's algorithm performs well, but is constrained to a maximum of three base stations, and it cannot fully exploit redundant measurements from additional anchors. Even worse, if one measurement of TDoA contains a huge error, the positioning result of Fang's method will be highly affected and become very inaccurate.

Considering the extensibility of the hardware platform, Taylor was selected because the system could provide a good initial estimate using auxiliary ultrasound/UWB ranging, improving convergence. If the hardware system can generate an initial position estimation by auxiliary sensing methods such as lidar, ultrasound or UWB ranging modules, the primary measurement of the starting point can be implemented into the Taylor iteration. In this case, the computational efficiency can be improved with a strong robustness in practical environments.

4. Conclusion

This paper introduces a UWB-based TDoA localization system with hardware basement and algorithm optimization. Although UWB communication has strong advantages in short-range tracking, like wide bandwidth, low latency and high ranging resolution, the practical accuracy in the real-world environment is still affected by many aspects, like antenna delay, clock drift, multipath propagation and measurement noise. In this case, the localization system requires both a precise hardware platform and a suitable algorithm to enhance robustness.

In the hardware verification, UWB modules with DW1000 chips carried were tested. The results showed that the raw measurements contained errors and offsets, which are mainly caused by antenna transmission and reception delay. By using two modules at a given distance as a reference, sweeping the antenna delay, and generating a compensation value, the ranging result was significantly improved. This verifies the antenna calibration is an essential step before applying the localization method. Another test with two-anchor positioning was also implemented to calculate the movement of the tag approximately matched the real movement and provide a feasibility of the hardware system using a multiple-number-of-anchors scheme.

For the algorithm verification, this paper confirms a TDoA mathematical model and used MATLAB simulation to compare the performance of three distinctive methods, Fang's, Chan's, and Taylor's algorithms. Fang's algorithm provides a simple closed-form solution, but it is limited to three-anchor cases and cannot fully use redundant anchor information. Chan's algorithm performed best under additive white Gaussian noise because its two-stage least-squares structure can efficiently use multiple anchors and provide accurate non-iterative estimation. However, its improvement becomes limited when the number of anchors is increased beyond a certain level, and its performance decreases in more complex channel environments.

Taylor's algorithm showed stronger robustness under the COST259 multipath channel model. Although it requires a good initial position estimate, its iterative correction process makes it more adaptable to non-Gaussian noise and practical propagation conditions. Therefore, the most effective solution is a hybrid framework: calibrated UWB hardware provides reliable TDoA measurements, Chan's algorithm generates an efficient initial estimate, and Taylor's algorithm refines the final position.

In general, accurate UWB TDoA localization cannot solely depend on hardware or on algorithms. A combination method is required. With DW1000 and auxiliary ranging modules, hardware basement and Taylor's algorithms refinement, the system can achieve better accuracy, stability, and practicality for real-time positioning and tracking applications based on microcontroller platforms. Future work should include full multi-anchor experiments, non-line-of-sight mitigation, and the research of auxiliary ranging devices.

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