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A review of UWB indoor positioning

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A review of UWB indoor positioning

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Abstract. With the development of science and technology, more accurate and stable location information can better serve people's lives. As people spend more time indoors, traditional positioning technologies such as Wi-Fi can no longer meet their needs due to a lack of positioning accuracy and interference resistance. UWB is an emerging positioning technology with high accuracy, robustness, and stability. This paper compares the advantages and disadvantages of UWB technology with those of Bluetooth and Wi-Fi. Common UWB geometric positioning methods such as TOA, TDOA, etc. are introduced. By introducing the latest research progress in UWB indoor positioning, an outlook on the future development of UWB indoor positioning is made. Compared with Bluetooth and other indoor positioning technologies, UWB positioning technology has the advantages of high positioning accuracy and good anti-interference. The UWB positioning system usually uses TOA, TDOA, AOA, and other positioning algorithms. In the future, UWB positioning technology will serve more and more complex positioning environments.

Keywords: UWB, indoor positioning, TOA, AOA, TDOA.

1. Introduction

Along with the development of science and technology, location-based services have entered every aspect of human life. UWB technology has a high potential for solving indoor positioning problems due to its stability and anti-jamming capability.

Ultra-Wide Band (UWB) was approved by the FCC in 2002 for operation in the public frequency band and requires strict compliance with the 3.1GHz-10.6GHz communication band. In the recent 20 years, UWB technology has received widespread attention and experienced rapid development due to its high accuracy, reliability, high resolution, and strong anti-interference characteristics. UWB technology has become a popular method for improving indoor positioning technology [1].

This paper first introduces the working principle of UWB and compares UWB technology with other common indoor positioning techniques, analyzing the advantages and disadvantages of different positioning techniques. The paper then introduces and compares several different geometric positioning techniques and models. Finally, the shortcomings of UWB and future development expectations are analyzed by presenting the latest advances in UWB indoor positioning technology in recent years [1, 2].

2. Indoor positioning technology

With the continuous development of wireless technology, indoor positioning technology and wireless positioning technology continue to combine. On the one hand, indoor positioning technology has undergone rapid development. On the other hand, a large number of wireless positioning technologies are in indoor positioning systems to give full play to their advantages, which are prominent: Bluetooth, Wi-Fi technology, infrared technology, ultra-wide band, etc.. Different technologies have different advantages and disadvantages and are used on different occasions.

Wi-Fi and Bluetooth are currently the most widely used technologies, as they require less equipment. Wi-Fi positioning uses the nearest neighbor method, or cross-location, which is less expensive but only determines the approximate location of the target object [3]. Bluetooth technology, on the other hand, relies on the small size of the Bluetooth system and is easy to integrate, but Bluetooth signals are very susceptible to environmental interference, especially from human factors. To improve accuracy, a dense arrangement of Bluetooth LAN base stations is required, which leads to increased costs [4].

Ultrasonic indoor positioning technology relies on the penetration and immunity of ultrasound itself, and the easy availability of concentrated acoustic energy allows for very high accuracy in small-scale positioning. However, it is difficult to achieve large scale positioning due to multipath effects, non-visual errors, and rapid signal degradation [5]. Infrared technology is also highly accurate but has high environmental requirements, as the environment and heat and light sources can affect the accuracy of positioning, and it is far less effective in more obscured environments than in more open ones. It is also not easy to implement, as infrared systems are more complex to arrange and require multiple infrared generators [6]. Radio frequency technology, according to the use of different frequency bands of the electromagnetic wave can be applied to more detection conditions and environments. Compared with ultrasonic and visible light positioning, radio frequency identification technology has the advantage of being relatively unaffected by the line of sight environment, and at the same time, it has high positioning accuracy and a high transmission rate. However, since a large number of radio frequency transmitters need to be arranged, the cost is very high and the convenience is not high [7].

UWB technology is an emerging radio communication technology in recent years that calculates the location of a tag based on the geometric relationship between the base station and the tag through communication between the base station and known location information. UWB technology has the characteristics of good robustness, strong resistance to interference, strong resistance to multipath effect and accurate positioning compared to other technologies. However, UWB indoor positioning systems are more complex than other positioning systems and therefore more costly to implement [2, 7].

3. Geometric distance measurement methods

Estimating the location of the tag consists of two main steps; the first is to determine a model of the relative relationship between the tag and the base station, and the second is to build a system of equations based on the model to estimate the location using a positioning algorithm. Common models include TOA, AOA, RSSI and TDOA.

3.1. TOA

The Time-Of-Arrival (TOA) is the most common model in traditional ranging, which uses the time of flight of a wireless signal to estimate the distance between the base station and the tag. There are two common TOA methods, one measures the single time of flight of the signal and multiplies it by the speed of the signal flight to obtain the distance, while the other method measures the round-trip time of flight of the signal [8].

The One-Way time-of-flight Arrival based ranging method (OWR) is based on the principle shown in Figure 1. Under the condition that the clocks of the base station and the tag are synchronized, a tag sends a signal to its area at time, and a base station in the area receives the signal at time, so the distance between the tag and the base station is given by:

$$d_s = c \times (t_b - t_{aj}) \tag{1}$$

In which c represents the speed of light, and t_{bi} represents the time stamp when the i base station (i=1,2, 3...) received signal. t_{a_j} is the time stamp when the tag transmits the signal. The OWR ranging system is simple to implement and there is no limit to the number of tags with measurements. But everything has to be achieved with a high degree of synchronization between the base station and tag clocks, so it is difficult to implement in practice.

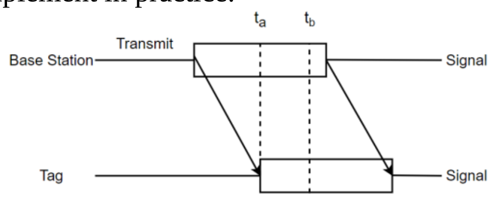

Figure 1. Principles of OWR.

The Two-Way time-of-flight Arrival (TWR) based ranging method is shown in Figure 2. The TWR method requires signal communication between the tag and the base station, unlike OWR, which uses a uniform device timestamp for its calculations to effectively avoid the problems associated with the inconsistent tag and base station clocks.

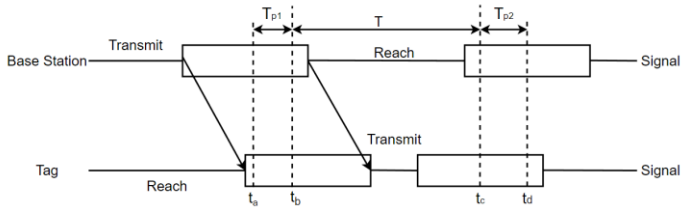

Figure 2. Principles of TWR.

In the process, the base station first transmits a ranging signal after a period of time t_0 after the tag i in t_b to receive the signal (i = 1, 2, 3, ...). After a period of time T, the tag in t_{ci} to send a response signal. The base station in t_{di} time to receive the signal. Use T_{P_1} to denote the time between the time the base station transmits the signal and the time the tag receives it, and T_{P_2} to denote the time the tag transmits the signal, and the base station receives it. Theoretically T_{P_1} should be equal to T_{P_2}, so we can get:

$$d_d = c \times T_{P_1} = c \times T_{P_2} \tag{2}$$

$$T_{P_1} = t_{b_1} - t_{a_1} \tag{3}$$

$$T_{P_2} = t_{d_1} - t_{c_1} \tag{4}$$

$$d_d = \frac{1}{2} \times c \times \left[\left(t_{b_1} - t_{a_1}\right) + \left(t_{d_1} - t_{c_1}\right)\right] \tag{5}$$

The TWR method solves the problems of synchronizing the tag and base station clocks on the one hand, and the number of tags on the other. As the base station can only communicate with one particular tag at a time, this limits the number of tags that can communicate at the same time.

From the principle of three-dimensional geometry, the distance from the tag to be measured to the base station is the radius, the base station is the center of the ball to make a ball, and different base stations for the center of the ball will intersect at a point. The location of the base station is usually used to locate four base stations. The above principle is shown in Figure 3:

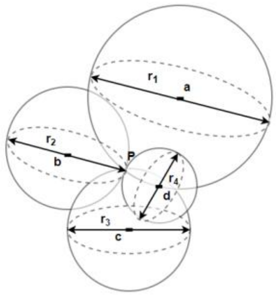

Figure 3. Geometric relations for TOA positioning.

As is shown in FIgure 3 that P is the locations of the tags to be measured, respectively, and the four base stations whose locations are known by their three-dimensional coordinates are:

$$\begin{cases} a(x_1, y_1, z_1) \\ b(x_2, y_2, z_2) \\ c(x_3, y_3, z_3) \\ d(x_4, y_4, z_4) \end{cases} \tag{6}$$

The distance between the four-base station to the tag is r_1, r_2, r_3, r_4. Let the three-dimensional coordinates of the base station be $p(x_0, y_0, z_0)$and we can get:

$$\begin{cases} r_1^2 = (x_1 - x_0)^2 + (y_1 - y_0)^2 + (z_1 - z_0)^2 \\ r_2^2 = (x_2 - x_0)^2 + (y_2 - y_0)^2 + (z_2 - z_0)^2 \\ r_3^2 = (x_3 - x_0)^2 + (y_3 - y_0)^2 + (z_3 - z_0)^2 \\ r_4^2 = (x_4 - x_0)^2 + (y_4 - y_0)^2 + (z_4 - z_0)^2 \end{cases} \tag{7}$$

Therefore, the following is a condensed formulation for the distance to the nth base station:

$$r_n = \sqrt{(x_n - x_0)^2 + (y_n - y_0)^2 + (z_n - z_0)^2} \tag{8}$$

3.2. TDOA

Like the time-of-arrival-based method TOA, Time Difference Of Arrival (TDOA) also uses the time of signal propagation in the air to achieve ranging. The difference is that instead of measuring the distance between a base station and the tag to be measured, TDOA needs to measure the distance difference between several different base stations to the tag distance to be measured to achieve the tag location. The principle is shown in Figure 4:

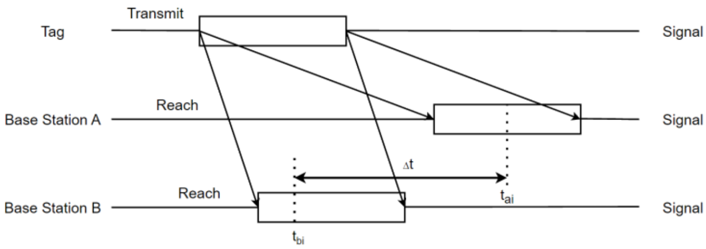

Figure 4. Principles of TDOA.

Use $d_a$and $d_b$to represent the distance from the base station A and B to the tag to be measured, c to represent the speed of light, and Δt to represent the time difference between the two base stations receiving the signal. So, the following equation for the distance difference can be obtained:

$$d_b - d_a = c \times \Delta t \tag{9}$$

The TDOA method does not require signal synchronisation between the tag and the base station, nor does it require the tag to communicate with the base station; it only requires the tag to send information to the base station. The TDOA method is shown in Figure 5:

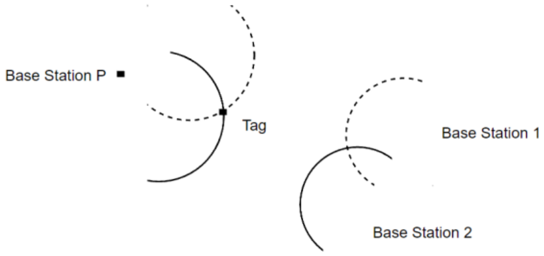

Figure 5. Geometric relations for TDOA positioning.

A base station P is selected as the main base station with coordinates (x_0, y_0), set the tag coordinates as (x, y) and the other base stations coordinates as (x_i, y_i). The above coordinates should satisfy the following equation:

$$r_{0i} = r_i - r_o = \sqrt{(x_i - x)^2 + (y_i - y)^2} - \sqrt{(x_0 - x)^2 + (y_0 - y)^2} \tag{10}$$

The distance between the first base station and the tag to be measured and the distance difference between the base station and the tag to be measured are denoted by. The principle of the model is: the distance difference between the tag to be measured and the different base stations has been obtained, usually a base station is selected and the distance difference between the second base station and that base station to the same tag is found, respectively. If the distance difference between two base stations and the base station is measured, two sets of hyperbolas can be obtained, and the intersection of the two sets of hyperbolas is the location of the tag to be measured [8-9].

3.3. AOA

When using the Angle Of Arrival (AOA) positioning system, it is typically necessary to set up the antenna array for angle identification, ranging in accordance with the various signals, and the horizontal axis formed by the angle of incidence reverse extension so that they intersect at a point, the point being the location of the tag to be measured, according to the specific principle illustrated in Figure 6:

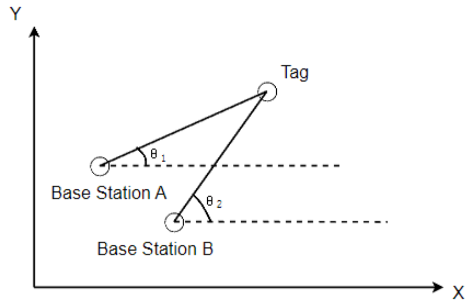

Figure 6. Principles of AOA.

The coordinates of the base station are (x_1, y_1),the coordinates of the base station are (x_2, y_2), let the coordinates of the tag be (x, y), the three should satisfy the following relationship equation:

$$\begin{cases} \tan\theta_1 x - y = \tan\theta_1 x_1 - y_1 \\ \tan\theta_2 x - y = \tan\theta_2 x_2 - y_2 \end{cases} \tag{11}$$

So, the N base station (x_n, y_n) should follow:

$$\tan\theta_n x - y = \tan\theta_n x_n - y_{2n} \tag{12}$$

There are N(N>2) base stations in the area. The incidence angle of each tag to the base station is θ_n, the coordinate of each base station is (x_n, y_n), according to the above relationship for the coordinates of the tag to be measured. The AOA method also avoids the problem of unsynchronized tag and base station clocks and is easy to implement, but it requires a large number of antenna matrices to be arranged and the cost is relatively high.

3.4. RSSI
The RSSI algorithm is based on the idea that a signal gets weaker as it moves through space. Therefore, the following equation holds true for the power received by the tag and the signal's distance:

$$P_b(S) = \frac{P_i G_j G_{bz} \lambda^{\tau}}{(4, \pi s)^{\tau}} \tag{13}$$

Where P_b is the frequency of the signal received by the tag, P_i is the transmit power of the signal transmitted by the base station, S is the distance transmitted, G_j is the gain when the base station transmits the signal, G_{bz} is the signal gain when the tag receives the signal, λ is the wavelength of the signal, and τ is the regional environmental path loss factor.

The RSSI method also does not require a high degree of synchronization between the base station and tag clocks because it is independent of time, but the loss and loss factor of the signal during propagation are greatly influenced by the environment, and subtle changes in the environment can lead to large changes in the results, so the error in the data is larger, and the resulting positioning error is larger [10].

3.5. Double-sided Two-way Ranging
The accuracy of ranging using various signal bandwidths varies, however UWB positioning systems using TOA or TDOA methods are substantially superior to AOA and RSSI methods because UWB has a very wide frequency domain signal with strong temporal resolution [11].

The TOA method only requires the measurement of the time stamp at each point in the process, after which the transmission time TOF of the signal is used for ranging. However, a TOF signal measurement time mistake of 1ns can result in a 30cm or even greater distance error. This is caused by system clock jitter due to crystal drift. It is therefore necessary to ensure that the clocks of the tag and the base station are highly synchronized. This is often difficult to achieve the desired synchronization in a practical environment or adds significantly to the complexity of the system, so a direct calculation of TOF can lead to large measurement errors. The bilateral bi-directional ranging method uses TOA as the basis for optimization and improves accuracy without the need to ensure that the tag and base station clocks are highly synchronized [11].

The bilateral bi-directional ranging method requires separate communication between the tag and the base station, i.e., one bilateral bi-directional ranging with all base stations in one cycle, and is shown in Figure 7:

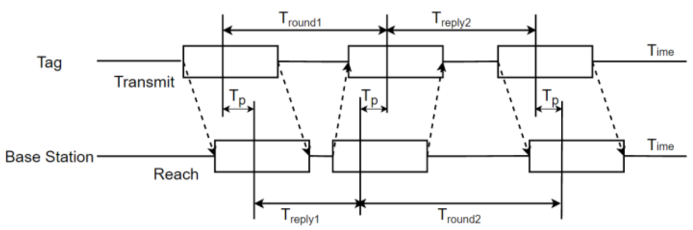

Figure 7. Principle of Double-sided Two-way Ranging.

The noise of the DS_TWR algorithm comes mainly from the timestamp accuracy of the RF chip, non-data effects, and the effects caused by multipath effects. The error introduced by its clocking can be expressed as follows:

$$\Phi = T_p \times \left(1 - \frac{k_1 + k_2}{2}\right) \tag{14}$$

Where $k_1$and k_2 denote the ratio of the actual frequency to the theoretical maximum frequency of the base station clock and tag clock respectively, both of which should be between 0.99998 and

1.00008. Assuming that the clock accuracy of the tag and the base station is poor, both are 10ppm level, let the distance between the base station and the tag be 10m, based on the speed of light as 3×10^8m/s to calculate, T_p should be 33.333ns, so the maximum value of Φ obtained according to the maximum value of k_1 and k_2 is 0.2mm, which can be neglected.

4. The development of UWB

4.1. Advantages and disadvantages of UWB

After 20 years of development, UWB has now received a lot of attention. From the point of view of current developments, UWB has many advantages: Firstly, UWB has high positioning accuracy. Secondly, UWB positioning has very low positioning latency. Thirdly, the UWB positioning technology is highly resistant to multipath effects. Finally, UWB system has high system robustness [7].

However, UWB indoor positioning technology is currently facing many difficulties:

Firstly, the price of positioning base stations and tags for UWB systems is significantly higher than the price of tags and base stations for other positioning systems. The quantity of base stations has an impact on positioning precision; hence, striving to increase accuracy also raises expenses. The quantity of base stations has an impact on positioning precision, hence striving to increase accuracy also raises expenses [12].

Secondly, it has high research and development difficulties. Most of the current UWB positioning systems use the DW1000 chip, and there are currently fewer algorithms based on the DW1000 chip. Problems such as positioning errors are dependent on algorithm optimization, which can greatly increase costs [7].

4.2. Recent advances in UWB

Recent developments in UWB have focused on how to suppress non-line-of-sight errors, improve algorithm accuracy, and increase positioning accuracy while controlling system complexity and cost.

The biggest issue now affecting UWB placement is the main system's low theoretical cost but high actual cost. According to known geometric positioning methods, reducing the number of base stations, i.e., anchor points, can reduce the computational effort of the algorithm and can reduce the problem of timestamp synchronization in the TOA method. The use of a single anchor point reduces the cost of the hardware on the one hand and the software algorithm on the other.[7, 13]

In addition to the higher cost, UWB positioning is susceptible to non-city errors. A TOA-based approach using Kalman filtering to suppress non-line-of-sight errors was used to improve the accuracy of 3D TOA positioning by Dongchen Ni et al. a new pedestrian heading projection (PDR) assisted UWB indoor positioning was proposed by Ming Xia et al.[9]. The researchers used the distance difference between UWB and PDR to calculate an accuracy factor model for the non-visual range error. This accuracy factor model was used to determine whether the UWB could be accurately positioned, and if this threshold was exceeded, the PDR was used instead of the UWB. The researcher's experiments showed that this method could significantly improve the positioning accuracy of the UWB. [14-16]

Unlike Josef Kulmer et al. who used a single anchor point Alwin Poulose et al. chose to use multiple anchor points [12]. Alwin Poulose et al. propose an indoor position estimation device using the extended Kalman filter (EKF) [2]. In their simulations they use methods such as least squares estimation for comparison and the results shows that the use of the extended Kalman filter (EKF) with aided indoor positioning systems can help improve the accuracy of UWB indoor positioning while reducing the complexity of the system for the same number of anchor points.

5. Conclusion

This paper summarizes the current common indoor positioning methods and compares their advantages and disadvantages. It is noted that the paper focuses on common geometric positioning methods for UWB and their recent development. The dominant geometric positioning method for UWB is now well established and will not change significantly with minor optimization. Optimization of UWB positioning should be based around suppressing non-visual errors and optimizing the positioning algorithm around the DW1000 chip. Judging from the speed and interest in UWB, UWB indoor positioning has a high scope for development and potential economic benefits.

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