Applications of UWB Positioning Technology in Smart Home

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Abstract. With the development of society, the modern demand for location information acquisition is gradually rising, and people's activities in indoor environments are also increasing. Indoor technologies such as Bluetooth and Wi-Fi can hardly meet the demand for high-precision indoor positioning, and thus cannot fully demonstrate the advantages of modern smart homes. This paper investigates the principle of UWB positioning technology and its wide applications in the smart home sector. This paper examines in detail the working principles of the positioning method in UWB ultra-wideband wireless technology to explore its significant advantages over other wireless technologies. At the same time, applications in a number of areas such as ranging, health, tracking, imaging, and RF marking, are proposed. It is shown through this research that the use of UWB positioning technology can provide a strong technical backdrop for the development of the smart home sector.

Keywords: Ultra-wideband · TOA/TDOA positioning algorithms · indoor positioning · wireless technology · smart home

1 Introduction

With the development of society, modern society enters the era of mobile Internet of Things, and the accurate acquisition of the spatial location information is a cutting-edge topic in the field of contemporary information science [1]. According to the different application scenarios, the current positioning technology can be divided into two types: indoor positioning techniques and outdoor positioning techniques. In the outdoor environment, the application of satellite positioning techniques can meet practical needs of people. However, in the indoor environment, due to multipath effects, the satellite positioning signal is constantly attenuated, resulting in low positioning accuracy, and even positioning failure [2]. With the development of society, people's activities in indoor environments are increasing, and indoor technologies such as Bluetooth, Wi-Fi can hardly meet the demand for high-precision indoor positioning [3], so it is important to study high-precision indoor positioning technology.

Ultra-wideband (UWB) wireless technology is a precise and efficient wireless positioning technology that achieves positioning by transmitting nano- to microsecond non-sinusoidal narrow pulses, which is generally applied to various indoor and outdoor

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environments, with the advantages of low power consumption, strong penetration, low system complexity, good privacy, and good confidentiality.

This paper first explains the working principle of UWB positioning technology, then compares it with other wireless technologies to summarize the significant advantages of UWB positioning technology, and ultimately facilitates the exploration of the future development trend of UWB technology in the smart home sector. Through this paper, academic research related to UWB positioning technology is enriched, and the advantages of this technology are better recognized, which also provides a relevant technical foundation for the application of this technology in the smart home field.

2 Related Work on UWB

Similar to existing wireless positioning technologies, UWB positioning is also accomplished through ranging and lateral direction. It generally consists of three methods: AOA (Angle of Arrival) based estimation, RSS (Received Signal Strength) based estimation, and TOA/TDOA (Time/Time Difference of Arrival) based estimation [4].

2.1 AOA (Angle of Arrival) Based Estimation

The AOA positioning method that uses an array of antennas to sense the direction of arrival of the electrical signal at the transmitting node, and then calculates the relative orientation between the receiving and transmitting nodes. To improve the positioning accuracy of the AOA method, antenna arrays are usually used, commonly known as uniform line arrays, uniform circular arrays, and cross arrays.

Although the principle of the AOA positioning method is very simple, this estimation method does not reflect the advantages of the large bandwidth and high temporal resolution of UWB signals. Under the current UWB multipath channel, the multipath signal is severely scattered by environmental objects, making it difficult to guarantee AOA accuracy. At the same time, the use of antenna arrays will undoubtedly increase the hardware size and cost of the system, making it difficult to promote in practical applications. The measurement accuracy of AOA also decreases with the increase in distance between the target node and the reference node, so the AOA estimation method is difficult to achieve accurate positioning.

2.2 RSS (Received Signal Strength) Based Estimation

RSS positioning method is based on the known wireless signal transmission power and channel propagation model. The reference node calculates the signal propagation loss based on the received signal strength, and then infers the distance valuation from the target node to the reference node to achieve the positioning of wireless users. It is a distance-based positioning technique.

UWB signals occupy an extremely large bandwidth and can achieve much greater positioning accuracy than traditional narrowband and wideband signals. However, in the RSS positioning principle, its ranging accuracy is not directly related to the signal bandwidth, and although measured distances can be obtained, the positioning advantages

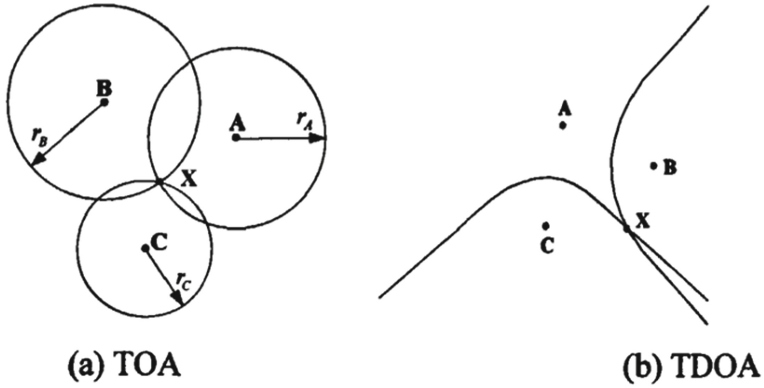

Fig. 1. TOA, TDOA positioning principle

of UWB signals cannot be exploited. The received signal strength method is dependent on the characteristics of the channel, and this method is strongly influenced by the estimation of the channel parameters. The RSS method is therefore only suitable for sites where the requirements for positioning accuracy are not high and there are few surrounding scatters.

2.3 TOA/TDOA (Time/Time Difference of Arrival) Based Estimation

The Time of Arrival (TOA) method is implemented by measuring the radio signal transmission time characteristics between the target node and the reference node. As an example of simple two-dimensional positioning: the principle of TOA and TDOA positioning is given in Fig. 1 (a) and (b), where A, B, and C denote the Reference Node (RN) and X denotes the Unknown Node (UN). The distance between the reference node (RN) and the unknown node (UN) can be determined by completing the TOA estimation. If the position of the RN is known, the position of the UN can be determined on the circumference of the circle with the RN as the round; the TDOA approach is slightly different in that two RNs are needed to obtain a time delay difference estimate, and the UN position trajectory is one of the hyperbolas, which depends on the sequence of the UN arriving at the RN end. From the figure, it can be concluded that at least three RNs are required to complete 2D positioning in the TOA/TDOA positioning method.

In practical positioning applications, the main difference between the TOA and TDOA methods is whether or not both transceivers need to be synchronized. For TOA, both positioning parties must synchronize the clock, and the clock deviation can easily affect the positioning performance of TOA. For TDOA positioning, both positioning parties do not need to synchronize, but the positioning measurement needs to be synchronized on the RN side.

3 UWB System Positioning Algorithm

3.1 TDOA Positioning

TDOA positioning is similar to TOA, but TDOA does not have the same strict clock synchronization between the target and the microcomputer station as TOA. The specific algorithm formula is as follows. Assuming that there are N positioning base stations BS1, BS2, BS3…BSn with a spacing to the target of D1, D2, D3…Dn, the formula is as follows:

$$\begin{gathered}\sqrt{(X_2-X_0)^2+(Y_2-Y_0)^2}-\sqrt{(X_1-X_0)^2+(Y_1-Y_0)^2}=D_2-D_1\\ \sqrt{(X_3-X_0)^2+(Y_3-Y_0)^2}-\sqrt{(X_2-X_0)^2+(Y_2-Y_0)^2}=D_3-D_2\\ \cdots\cdots\cdots\cdots\cdots\\ \sqrt{(X_n-X_0)^2+(Y_n-Y_0)^2}-\sqrt{(X_{n-1}-X_0)^2+(Y_{n-1}-Y_0)^2}=D_n-D_{n-1}\end{gathered} \tag{1}$$

(X_0, Y_0) are the coordinates of the target to be located. (X_n, Y_n) are the coordinates of each base station. D_n is the distance between each base station and the target estimated from the TOA data.

3.2 Positioning Algorithms

TDOA positioning is based on the principle of calculating the time difference, which best highlights the advantages of the high temporal resolution of UWB signals. The implementation of the TDOA positioning algorithm based on time difference of arrival is divided into 3 main steps. The first is to estimate the measured value T of the UWB signal sent by the tag to reach the base station based on the time delay. The second is to calculate the distance d from the TDOA and then combine the systems of equations. The third is that a sphere positioning method is adopted to calculate the position of the tag to be positioned.

For example, if the base station receives a UWB signal from a tag with a time delay of TD, the straight line distance between it and the base station is D = TD*C (C = $3*10^8$ m/s). Based on geometric knowledge, with the base station as the round of a circle and the tag on a circumference with D as the radius, the relationship between the position of the UWB tag (x, y, z) and the base station (x_i, y_i, z_i) satisfies the following system of equations.

$$\begin{gathered}(x_1-x)^2+(y_1-y)^2+(z_1-z)^2=d_1^2\\ (x_2-x)^2+(y_2-y)^2+(z_2-z)^2=d_2^2\\ \cdots\cdots\cdots\cdots\\ (x_i-x)^2+(y_i-y)^2+(z_i-z)^2=d_i^2\end{gathered} \tag{2}$$

4 Advantages of UWB Positioning Technology

4.1 High Positioning Accuracy

At present, in the field of wireless positioning, commonly used positioning technologies are Proximity cards, GPS, Bluetooth, IEEE802.11, Dedicated RF, Uni directional UWB

Table 1. Positioning accuracy of commonly used wireless positioning technologies

Positioning Technology	Proximity cards	GPS	IEEE802.11	Dedicated RF	Uni directional UWB	UBI sense UWB
Accuracy	5 m ~ 20 m	About 3 m	About 3 m	About 3 m	less than 30 cm	15 cm

Table 2. Real-time response of commonly used wireless positioning technologies

Positioning Technology	Proximity cards	GPS	IEEE802.11	Dedicated RF	Uni directional UWB	UBI sense UWB
Real-time response	0–001 Hz	About 0–1 Hz	0–2 Hz	0–4 Hz	0–1 Hz/1 Hz	40 Hz

and UBI sense UWB. The positioning accuracy of various commonly used wireless positioning technologies is shown in Table 1, which shows that the positioning accuracy of UWB positioning technology is much higher compared to other wireless positioning technologies.

4.2 Wide Range of Coverage

Compared to other wireless positioning technologies, UWB positioning technology has a wider coverage area and is very effective in the construction of real-time positioning systems for indoor environments. If the coverage area is to be extended, multiple positioning units can be used in combination to increase the coverage area and thus meet the requirements of practical use.

4.3 Good Real-Time Performance

UWB positioning technology is characterized by good real-time performance, which is a significant advantage over other positioning technologies. The real-time response frequencies of various commonly used wireless positioning technologies are shown in Table 2. From the table, it can be seen that UWB technology has a clear advantage over other wireless positioning technologies in terms of real-time performance.

4.4 High Penetrating Power

UWB has a very strong signal penetration capability. Its signal can penetrate concrete, soil, water, and leaves, which makes it widely used in military and civilian applications. For example, in the military sector, radar powered by UWB technology can be used to detect landmines; in the civilian sector, it can be used to detect highway foundations and find underground metal pipes, among many other areas.

4.5 High Transmission Capacity

UWB technology has very good transmission capabilities. In the civilian sector, UWB signals typically have a transmission range of 10 m or less and can be modified to achieve transmission rates of up to 500 Mbit/s by modifying the channel capacity formula, making it an ideal modulation technology for personal communications and wireless LANs. UWB's very wide frequency bandwidth allows UWB to transmit data at high speed and work together with other wireless technologies without occupying the already crowded frequency resources alone.

4.6 Low Transmitting Power

UWB technology sends data by means of intermittent pulses. The pulse duration is usually in the range of 0.2 ns to 1.5 ns. Even at high-speed communication, the power consumption of the system is only a few hundred uW to a few tens of mW [5]. Currently, the power of UWB devices for civilian use is very low, compared to traditional mobile phones, its power is only one hundredth of that of traditional mobile phones, compared to Bluetooth devices, which are around one twentieth of the power of traditional mobile phones, compared to Bluetooth devices.

4.7 Good Confidentiality

Due to its extremely powerful spectrum capabilities, UWB technology can be effective in providing confidentiality during its application. The broadband path for UWB communications must meet signal restrictions that reduce power while blocking other sources in the communications network. This blocking allows different communication signals to remain on their own channels, so that the ultra-wideband signal transmission does not conflict with other signals, but also solves the problem of signal interference and interception, and plays a good role in the confidentiality of communications.

5 Future Development Applications in the Field of Smart Home

In the smart home sector, UWB positioning technology can be used to pinpoint small and medium-sized items in the home, meet the positioning needs of various indoor environments, and work simultaneously with other signal frequencies to reduce cache content and avoid the working frequency of other wireless technologies. At the same time, the use of UWB positioning technology can reduce the power consumption of related equipment and increase battery life. In addition, UWB positioning technology can focus on a single user and does not lead to information leakage, thus enabling fast, accurate, effective and secure positioning services. The end result is a new home network [6].

5.1 UWB Ranging Applications

The latest FCC report opens up a wider band for UWB radar and sensor applications: 5.925 to 7.250 GHz, 16.2 to 17.7 GHz, and 23.12 to 29.0 GHz [7]. FONTANA, a leading scholar of UWB positioning research, summarizes UWB ranging applications in recent years [8, 9], categorizing them according to different accuracy needs into intrusion detection systems, anti-collision systems, and precision ranging systems.

For the smart home, Intrusion Detection is a rough ranging application, but it can monitor targets in a specific area of the user's location and alert objects outside the area. In simple terms, this means that when a stranger illegally enters an indoor premises, the equipment using UWB positioning technology can detect the intrusion and provide a timely warning, minimizing false alarms and missed alarms, enabling the user to respond in a timely manner and minimizing the associated damage.

At the same time, because UWB positioning technology has characteristics such as strong penetration, it can be used to detect targets (people) inside buildings or bunkers in a non-intrusive way from the outside and to detect moving targets inside buildings using an ultra-wideband through-the-wall detection radar (UWB-TWDR) system. In order to effectively capture the target echo signal and suppress clutter and interference, the penetration detection radar samples the echo signal only a short time after each transmitted pulse. The characteristics of the echo waveform can then be used to distinguish between targets of different shapes, sizes and dimensions as a basis for target identification. Therefore, the combination of intrusion detection system and UWB penetration detection radar system can complete the monitoring of illegal intrusion, so as to maximize the personal and property safety of users.

Obstacle Avoidance systems can be used in automated cruise systems, for example, and have a much higher target detection sensitivity than intrusion detection systems, with a range of up to 300 m. This technology can be applied to AI robots and other devices, enabling the robot to detect obstacles in its vicinity, react to them, and change its path in time to prevent an impact.

5.2 UWB Health Applications

In China, the number of older people is gradually increasing, and according to statistics, the ageing of China will peak by 2050, with 27.9% of China's population aged over 65 [10]. The demand for health-related services is therefore increasing proportionately, and many older people need healthcare services to improve and maintain their health status and autonomy within their families or communities. With occupational therapists or other healthcare professionals not only being expensive but also leading to a decline in the quality of human life, the development of health monitoring technology is an urgent necessity. Today's UWB positioning technology allows for small systems on a chip (soc) with low energy requirements [11]. In the area of health monitoring, UWB positioning technology is showing promise in providing independent living solutions for the elderly [12, 13].

Due to its characteristics such as high resolution and penetration, UWB positioning technology has been tested in a variety of radar applications such as target and motion monitoring, allowing for the completion of wearable technology. Good recognition results can be achieved through a range of wearable accelerometer-based human activity recognition methods.

However, most work today utilizes only one radar in a laboratory setup, and for the purpose of activity recognition in a real home environment, multiple radars are not implemented for deployment. So, by improving the algorithms and recognition methods, it will be possible in the future to achieve health monitoring of the entire smart home environment through the synergistic work of multiple radars.

5.3 UWB Tracking, Imaging Applications

The use of UWB positioning technology for bionic applications is currently a widely sought-after application area, such as bat-like positioning and imaging based on the characteristics of UWB signals, with a single transmitter and two receivers as sensors, transmitting UWB signals and receiving reflections from targets such as walls, edges, and corners to determine distances, identifying different targets based on different reflection characteristics, combining positioning and imaging, etc. The technology is a combination of positioning and imaging.

For the UWB location tracking system, it has a wider application. In case of emergency (such as indoor fire), it is impossible to use the existing facilities to understand the on-site situation and organize rescue. At this time, ultra wideband equipment is quickly networked to carry out low-speed communication and location tracking, and complete a series of processes such as search, guidance and monitoring, so as to quickly complete the rescue work and reduce losses.

5.4 UWB RF Marking Applications

Using the wide application of UWB technology in tracking applications, combined with its advantages of high speed, good confidentiality, and strong interception resistance, it is possible to achieve the management of documents and books in the home study, in the office, or study, so that each document and book (including e-books) is accompanied by a UWB radio frequency tag. Using the precise positioning ability of UWB, users can easily find the documents and books through PC, PDA, or other terminals.

Using the UWB's precise location capability, users can easily locate the desired documents and books via PC, PDA or other terminals. Users can also use their PDAs to download a multimedia catalogue of managed documents, and when a paper version of a document or book is selected, the specific location of that paper version can be found according to the catalogue. This application is also suitable for libraries to manage large numbers of books, thus reducing the need for manual checks and operations. The application can also be extended to household products, where the UWB radio frequency tag attached to the product can be used to detect its location at any time and use the catalogue to find its location, thus reducing unnecessary searching time and increasing efficiency.

6 Conclusion

This paper focuses on the TOA/TDOA positioning method in UWB positioning technology. Through the analysis of its algorithm, the multiple advantages of UWB technology are summarized and concluded, and the future development trend of UWB positioning technology in the specific field of smart home is proposed through detailed examples and predictions from the fields of ranging, tracking, imaging, detection and RF marking respectively, aiming to provide new directions for the next UWB. This paper only briefly describes the development trend of UWB positioning technology in the smart home sector, and does not extend the positioning algorithm much further.

In addition, future research will collect relevant databases and combine them with more relevant technical algorithms to avoid any impracticality in this study, so that it can provide better ideas for the development in the field of smart home.

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