Strategy to Improve the Positioning Accuracy of Bluetooth in a Complex Indoor Environment

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Abstract. Bluetooth positioning technology is vulnerable to multipath interference, signal occlusion and other factors in a complex environment, which cannot meet the requirements of high precision positioning. In order to improve the positioning accuracy of Bluetooth, this paper summarizes several technical principles of Bluetooth positioning, focusing on three key influencing factors: environment, hardware and algorithm. Then, through integrating the research results of recent years, this paper puts forward precision improvement strategies from three perspectives: hardware optimization, algorithm improvement and system design. The effectiveness of the technology is validated through real-world applications in commercial, industrial, and medical sectors. Finally, addressing technical bottlenecks in complex environments, this study explores future development directions such as multi-technology integration and intelligent algorithm iteration, providing theoretical and practical references for high-precision Bluetooth positioning applications in smart scenarios.

Keywords: Indoor navigation technology; Bluetooth positioning; Fusion positioning; Precision optimization; Complex environment.

1. Introduction

In the era of intelligent wave sweeping the world, indoor positioning technology has become a key link in the construction of a smart society. Traditional satellite positioning technology is easily limited by signal attenuation, multipath effect and other limitations in the room, which makes it difficult to meet the needs of high precision positioning. Therefore, it is of urgent practical significance to develop indoor navigation technology. Bluetooth positioning technology has become a research hotspot in the field of indoor navigation due to its advantages such as low power consumption, low cost and easy deployment.

At present, several core technologies of Bluetooth positioning have their own advantages, but also have inevitable limitations: RSSI technology estimates the distance through signal strength, and the signal is easily affected by environmental interference, resulting in poor stability and large fluctuation of accuracy; AoA/AoD technology uses antenna array to measure phase difference with sub-meter accuracy, but the reflection and scattering of signals will distort the measurement Angle and reduce the accuracy;ToF technology is based on time difference ranging, with high theoretical accuracy, but it requires very high clock synchronization, and a small time deviation will significantly reduce the accuracy;The accuracy of fingerprint positioning depends on the density of fingerprint database. The higher the density, the higher the accuracy, but also the higher the deployment cost. Additionally, the database will fail due to environmental changes and require frequent updates.

Although these technologies have been applied to scenarios such as shopping mall navigation, airport baggage tracking, and factory equipment management, the current indoor navigation technology still struggles to meet the precision requirements of high-end scenarios like industrial robot control and AR/VR positioning due to issues like multipath interference and non-line-of-sight propagation in complex indoor environments. This limitation has constrained the application and promotion of indoor positioning technology.

Therefore, this paper will study the principle of Bluetooth positioning and the strategy to improve the accuracy.By analyzing the core technologies such as RSSI, AoA, ToF and fingerprint

positioning, this paper summarizes the improvement strategies from three perspectives of hardware optimization, algorithm improvement and system design based on the influence mechanism of environment, hardware, algorithm and other factors on positioning accuracy.

The research results will help deepen the industry's theoretical understanding of Bluetooth positioning technology, and, more importantly, provide innovative ideas for solving the bottleneck problem of indoor positioning accuracy.

2. Basic theory of Bluetooth Positioning Technology

2.1. RSSI Positioning Principle

The positioning technology based on Received Signal Strength Indicator (RSSI) estimates the distance by detecting the Bluetooth signal strength received by the device, and needs to preset the signal attenuation model according to the corresponding relationship between the received signal strength and the distance. The advantage of RSSI positioning is that it only uses an ordinary BLE module without special hardware, but it is significantly affected by environmental interference. The error in complex indoor scenarios is usually 3-5 meters [1,2].

2.2. AoA and ToF Positioning Principles

AoA and AoD are high-precision positioning schemes introduced by Bluetooth 5.1.AoD determines target direction by measuring signal arrival angles through multi-antenna arrays on receivers, converting the signal's incidence angle based on time or phase differences between different antennas. AoA, conversely, involves transmitting signals via antenna arrays at the transmitter while receiving them with a single antenna at the receiver. The angular calculation method follows the same principle as AoA [2].

The ToF measurement accuracy supported by Bluetooth 5.1 can reach 1ns, corresponding to a distance error of about 0.15 meters, but it requires strict synchronization of the clock between the transmitter and receiver, and non-line-of-sight propagation will cause time measurement deviation.

The positioning accuracy of AoA/AoD and ToF technology can reach sub-meter level, but it requires special chips such as Nordic nRF52840 and antenna array, and the hardware cost and complexity are significantly higher than that of the RSSI scheme [3].

2.3. Fingerprint Positioning Principle

Fingerprint positioning technology can be divided into offline and online stages to realize positioning by constructing the mapping relationship between location information and signal features. In the offline stage, it is necessary to collect the location information and signal characteristics (such as RSSI value) of multiple points in the target area to form a fingerprint database. In the online stage, the real-time collected signal features are matched with the database, and the most similar signal features are matched by K nearest neighbor (KNN) and support vector machine (SVM), and the corresponding position is taken as the positioning result [2,4].

Fingerprint positioning does not require distance conversion, which can avoid systematic errors of the multipath effect. The accuracy can reach 1-2 meters in a stable environment. However, its performance depends on the integrity and timeliness of the fingerprint database. Environmental changes, such as personnel flow and equipment movement, will lead to the failure of the database, which requires regular calibration and time-consuming effort. In addition, regarding algorithm matching, machine learning technology has been used to optimize fingerprint matching in recent years. For example, neural networks can be used to fit the nonlinear relationship between signal features and positions, so as to improve the robustness in a dynamic environment and further improve the accuracy of fingerprint positioning [5-7].

The four positioning technologies are compared as shown in Table 1.

Table 1. Comparison of Bluetooth positioning technologies

Type of technology	Theoretical precision	Field-measured error	Power dissipation index	Typical scenario
RSSI fixed position	2-3m	3.5±1.2m	1.0	Shopping mall
AoA fixed position	0.3m	0.7±0.3m	4.8	Surgeon Tracking
ToF fixed position	0.2m	1.1±0.5m	3.2	Industrial robot
Fingerprint positioning	1.5m	2.3±0.8m	1.2	Smart Warehouse

3. Factors Affecting the Positioning Accuracy of Bluetooth

3.1. Environmental Factors

The multipath effect is the main source of positioning error in a complex indoor environment. During propagation, the Bluetooth signal is reflected and refracted by walls, furniture and other objects to form multipath components. The time difference of signals arriving at the receiver from different paths will cause a phase shift. When combined with direct signals, it will lead to fluctuation of RSSI value, which can reach 10-20dB range, breaking the monotonic relationship between signal strength and distance. Experimental data show that the multipath effect can increase the RSSI ranging error by 30%-50% [1,8].

Non-line-of-sight (NLOS) propagation caused by signal occlusion makes the signal unable to travel straight between the transmitter and receiver, and causes attenuation, delay and multipath effects due to reflection, refraction and scattering of obstacles. For example, the attenuation of the 2.4GHz signal in the human body is up to 8-15dB, and the attenuation caused by metal obstacles is even more than 20dB. Obstruction will lead to a large distance estimation and increase the measurement time. In crowded places such as shopping malls and hospitals, the positioning error will increase by 1-3 meters [9].

Environmental dynamic changes, such as temperature, humidity, personnel flow, etc., will affect the signal propagation. Every 10℃ change in temperature, signal attenuation will change by 2%-5% due to the change in air dielectric constant. The movement of personnel or equipment will change the signal propagation path, resulting in new reflection or occlusion, and produce deviation from the fingerprint database data. For example, during the morning rush hour of the mall, the fingerprint positioning error will increase from 1.2m to 2.8m, resulting in a decrease of 20%-40% in the fingerprint positioning accuracy [10][11].

3.2. Hardware Factors

Bluetooth chip performance is an important factor affecting measurement accuracy. Taking TI CC2540 and Nordic nRF52832 as an example, the RSSI measurement deviation between them can reach 7dB, which will make the distance estimation error double the original one. For example, ToF positioning requires high clock stability of the chip. A clock deviation of 1ppm will cause a measurement error of 0.3m for every 100 meters of distance [12].

Antenna design is an indispensable point for AoA/AoD technology which depends on the antenna. Antenna gain should be distributed according to the demand. High gain covers a wide area but reduces accuracy, and low gain is only suitable for small areas of accurate positioning.The array layout of the antenna will directly affect the resolution of the Angle measurement, and the unreasonable distribution will lead to phase blur and increase the calculation error.In addition, the mismatch between the polarization direction of the antenna and the propagation direction of the signal will also lead to a decrease in the received signal strength and further amplify the error [12].

The stability of signal transmission power also affects the positioning accuracy.For RSSI positioning, if the transmission power is suddenly enhanced, the receiver will misjudge that the

terminal is closer, and vice versa, when the power attenuates, it will misjudge that the distance is farther, which will reduce the accuracy of positioning algorithms such as triangle centroid.For AoA positioning technology, the signal is easy to be disturbed by noise when power drops, which increases the error of phase calculation and Angle calculation, and finally affects the accuracy of measured coordinates.A power fluctuation ±2dB will increase the distance error by 10%-15%, while the power attenuation caused by the drop of battery voltage, such as CR2032 battery from 3V to 2.5V, will decrease the power by 3dB, which will continuously deteriorate the long-term positioning accuracy.

3.3. Algorithmic Factors

Traditional positioning algorithms exhibit significant limitations in complex environments. The multilateral measurement method of Received Signal Strength Indicators (RSSI) is highly sensitive to outliers, where a single abnormal RSSI value from a Bluetooth beacon can double the positioning error. Conventional filtering techniques like Kalman filtering struggle with dynamic scenarios involving sudden occlusions, with filter lag potentially reaching 0.5-1 seconds [11].

Fingerprint positioning matching algorithm is significantly affected by environmental changes. KNN algorithm has obvious decrease in accuracy when the fingerprint database ages, while similarity measurement based on Euclidean distance cannot distinguish environmental interference from real position change, resulting in an increased matching error rate.

The weight allocation of the data fusion algorithm is unreasonable, which will affect the fusion effect.RSSI is unreliable when occluded, and IMU accumulates errors in long-term positioning. Therefore, if the real-time reliability of different technologies is not considered in simple weighted fusion, the fusion results may be worse than those of a single technology.

4. Research Progress on the Improvement Strategy of Bluetooth Positioning Accuracy

4.1. Hardware Optimization Strategy

4.1.1 Multiple-antenna technology

A reasonable multi-antenna array can significantly improve the measurement accuracy of AoA/AoD. By replacing the linear array (ULA) with a uniform rectangular array (URA) to achieve two-dimensional measurement of azimuth and pitch angles, the positioning accuracy can be improved by 40%-60% in complex space [2][3]. For example, the 4×4 URA can control the angular error within 3° in the laboratory environment, and the corresponding positional error at a distance of 10 meters is less than 0.5 meters [8].

Adaptive antenna selection technology can switch the optimal antenna for measurement according to the real-time monitoring of signal strength and SNR of each antenna, so as to adapt to environmental changes and improve anti-interference performance.This technology can improve the RSSI stability by 30% and reduce the positioning error by 0.5-1 meters in the walking scene [8].

Smart antenna beamforming technology can adjust the phase and amplitude of the signal through algorithms, so that the electromagnetic wave energy forms a directional beam, focusing only on the useful signal, thus reducing interference.In industrial workshop and other multi-device scenarios, beamforming can improve the signal-to-interference ratio (SIR) by 10-15dB, and the accuracy of ToF measurement signal enhancement technology can be improved by 20%-30%.

4.1.2 Signal enhancement techniques

The power control algorithm can dynamically adjust the transmission power to ensure signal quality while reducing interference and energy consumption, so as to maintain stable communication or positioning performance in complex environments.The low power of-20dBm is used to reduce the multipath reflection within 5 meters, and the signal strength is increased to 0dBm

at a distance of more than 10 meters. The experiment shows that the overall positioning error can be reduced by 15%-20%[2].

Optimizing channel coding can enhance signal anti-interference capability. By combining 1/2-rate convolutional coding with interleaving technology, the bit error rate (BER) can be reduced from 10^(-3) to 10^(-5),improving the stability of RSSI measurements in multi-interference environments and reducing fluctuation errors by 25%.

Adaptive frequency hopping technology can avoid the interference band. By monitoring the interference level of each channel in real time, clean channels are selected for communication. In Wi-Fi dense areas, the signal quality can be improved by more than 10dB and the positioning accuracy can be improved by 30%[6].

4.2. Algorithm Improvement Strategy

4.2.1 Data fusion algorithm

Bluetooth and IMU fusion can complement each other. Bluetooth positioning depends on external signals (such as beacons, base stations, etc.), which are prone to weak signal, fluctuation or even interruption in a complex indoor environment.The IMU can sense its own motion state through the accelerometer, gyroscope and other sensors. It can provide short-term positioning independently when the Bluetooth signal is lost, so as to avoid the discontinuity or jump of the positioning trajectory, so that it can carry out continuous, stable and accurate positioning in complex environments.The error can be reduced from 3-5 meters to 1-2 meters. For example, in the smart airport, the interruption rate of baggage car tracking is reduced from 25% to less than 5% by integrating Bluetooth and IMU [3,9,13].

The combination of Bluetooth and UWB can achieve a balance between accuracy and cost. UWB has strong anti-multipath effect but a high cost, while Bluetooth has wide coverage and low power consumption. The weight can be allocated according to environmental requirements through filtering algorithm. In scenarios with high accuracy requirements, UWB weight can be higher, while the Bluetooth weight is higher. For example, UWB accounts for 70% in line-of-sight scenarios and Bluetooth accounts for 60% in non-line-of-sight scenarios, which can achieve 0.3-meter accuracy in industrial shelf positioning and reduce the cost by 50% compared with pure UWB solutions [3][9].

Bluetooth and geomagnetic fingerprint fusion can improve stability. Different from Bluetooth, geomagnetic fingerprint positioning is not affected by the earth's magnetic field and can be used in complex environments. However, the positioning accuracy and specificity are not high when used alone, which can be compensated by Bluetooth positioning. Using this fusion positioning, the standard deviation of positioning error can be reduced from 1.2 meters to 0.6 meters in dynamic environments such as shopping malls, and the error of 95% confidence interval can be reduced by 40%[4][11].

4.2.2 Machine learning and deep learning algorithms

The fingerprint positioning model based on random forest can eliminate outliers by learning the correlation between signal and environmental interference in historical data, so that the mapping model of RSSI value and distance is more reliable. Experiments show that the positioning accuracy in office scene is improved by 25%, and the error is less than 1.1 meters [1].

Convolutional neural network (CNN) can extract deep signal features from the original RSSI sequence, convert the RSSI sequence into a two-dimensional matrix input to CNN, capture the pattern features of multipath effect, and process nonlinear and time-varying interference more efficiently. The accuracy of CNN is 50% higher than that of traditional KNN algorithm in multi-obscured scenarios [1].

Reinforcement learning can learn the changing patterns of the environment through "trial and error", such as adapting the frequency of fingerprint database update according to the difference in personnel distribution on weekdays or weekends, which can reduce the calibration workload by 60% in large shopping malls while keeping the positioning accuracy within 1.5 meters.

4.2.3 Filtering Algorithm

Adaptive Kalman filter (AKF) adds the function of real-time dynamic adjustment of noise covariance to the traditional Kalman filter. By adjusting Q and R matrices by real-time monitoring of residual variation, the filter failure caused by incompatibility with the fixed noise model can be avoided. In the fast moving scene, the filter lag is reduced by 60% and the trajectory smoothness is increased by 40%[1][8].

Particle filter (PF) approximates the actual position of the target gradually through a large number of weighted sample points, which is suitable for processing signals with strong nonlinear and non-Gaussian interference [8][13][14].In the multipath corridor scenario, the positioning error of PF algorithm is greatly reduced compared with EKF.

Sliding window weighted filter can assign different weights to the recent Bluetooth positioning data within the sliding time window (the recent data has higher weight), and output the result after weighted average, so it can suppress burst interference. For example, if the weighted average of the recent 5-10 RSSI values is carried out in the experiment, the signal fluctuation can be reduced by 50% in theory at the moment of personnel occlusion, and the positioning jump can be controlled within 0.5 meters [8-10].

4.3. System Optimization Strategy

4.3.1 Anchor layout optimization

Anchor layout based on greedy algorithm can maximize coverage accuracy. Taking the difference of fingerprint database as the objective function and iteratively optimizing the beacon position, in the experimental area of 65×17 meters, 7 anchor points can achieve positioning error less than 3 meters in 90% of the area, which is 2 anchor points less than the uniform layout [9][10].

Hierarchical layout strategy is suitable for complex spatial structure [14]. Ceiling beacons are deployed in halls with a height greater than 3 meters to increase coverage, wall beacons are deployed in corridors to reduce multipath, and ground beacons are deployed at elevator entrances to enhance vertical positioning. A well-adapted anchor layout can improve the positioning accuracy by 30% in the airport terminal scenario [3][10].

Dynamic anchor technology can supplement weak areas.By deploying portable beacons in temporary activity sites and integrating them into the system through Bluetooth Mesh self-organizing network, the local positioning error can be reduced from 4.5 meters to 2.0 meters [9][10].

4.3.2 Dynamic calibration and adaptive update mechanism

Online incremental learning can update the fingerprint database in real time.By fine-tuning the model with 10% of the newly collected data every hour, the effective period of the fingerprint database in the supermarket scene is extended from one week to one month, and the accuracy decay rate is reduced from 50% to 15%[10][11].

The environment-aware trigger calibration mechanism reduces redundant work.By monitoring the fluctuation variance of RSSI (when exceeding the threshold of 5dB), the calibration was automatically started, and the calibration frequency in hospital scenarios was reduced by 60%, while maintaining the accuracy within 1.8 meters [11].

Device adaptive calibration eliminates hardware differences.Through the joint measurement under the unified coordinate system, the RSSI conversion model of different devices is established, and the positioning consistency of multi-brand terminals is improved by 40%, and the standard deviation of error is reduced from 1.5 meters to 0.9 meters [9].

5. Application Case Analysis of Bluetooth Positioning Technology

5.1. Business Application Cases

In the navigation of large shopping malls, the positioning system based on Bluetooth 5.1 AoA technology is used to achieve sub-meter accuracy.By analyzing the user positioning trajectory, the layout of shopping malls can be optimized more scientifically. Theoretically, the passenger flow in hot areas can be increased by 20%, thus increasing the revenue of shopping malls [2].

The smart parking lot adopts the fusion of Bluetooth and UWB positioning to realize accurate vehicle guidance.80 Bluetooth beacons are deployed in the parking lot with 500 parking Spaces. After entering, vehicles can be preliminarily positioned through mobile phone Bluetooth, and the error is less than 2 meters.When approaching the parking space, it switches to UWB precise positioning, and the error is reduced to within 0.3 meters. The reverse car search time is reduced from 10 minutes to 1 minute, which can increase the parking turnover rate by 30% and increase the parking income [2][3].At the same time, it can reduce the cost of manual patrol guidance and reduce the management and operation expenses of parking lots. Car owners can also find their cars or parking Spaces through real-time positioning on mobile phones, which greatly improves the parking experience.

5.2. Industrial application cases

In the intelligent manufacturing workshop, the integration of Bluetooth and IMU is used for AGV robot navigation [13]. Fifty Bluetooth beacons are deployed in the workshop. By integrating Bluetooth position and IMU motion data, AGV can keep the positioning error within 0.5 meters in the scene of metal shelf occlusion, improve the path tracking accuracy by 40%, and reduce the collision rate of AGV from 3 times per month to 0 times [2].

In warehousing management, bluetooth fingerprint positioning can be used to achieve goods tracking.A fingerprint database with 5,000 reference points was established in the 10,000-square-meter warehouse. Using the random forest matching algorithm, the forklift positioning error is less than 1.2 meters, the inventory efficiency is improved by 50%, and the inventory accuracy rate is increased from 92% to 99%.

Real-time tracking of goods, AGV robots and staff location can not only optimize the transportation path of goods, reduce inventory backlog, wrong delivery, missed delivery and other situations, but also reduce the loss of production stoppage caused by inaccurate positioning, and reduce the cost of manual inventory.

5.3. Medical Application Cases

The hospital patient tracking system uses Bluetooth low power positioning technology.200 BLE beacons are deployed in the inpatient building. The patient wristband is located through RSSI, and the room location is determined by integrating the status of the door magnet in the ward. The positioning error is less than 2 meters, and the nurse response time is shortened from 10 minutes to 5 minutes [1][15]. According to the survey, it can be roughly inferred that the patient satisfaction increases by 25%.The system also supports emergency call positioning, the positioning response time is less than 1 second, optimize personnel scheduling, and give patients more timely treatment.

In the management of surgical equipment, Bluetooth AoD technology can achieve high precision tracking.8 antenna array beacons are deployed in the operating room, and the positioning error of surgical instrument labels is less than 0.3 meters. The equipment counting time is reduced from 30 minutes to 5 minutes, and the omission rate is reduced from 8% to 0%[2][15], which avoids the loss or wrong taking of equipment and reduces the cost of equipment reset.This reduces the preparation time and improves the utilization of the operating room.

6. Challenges and Future Development Direction of Bluetooth Positioning Technology

In complex indoor environment positioning, multipath interference is still an inevitable and difficult to suppress problem, the positioning error is difficult to control within 1m.It is often difficult to balance the high precision of positioning technology and the low power consumption of hardware.There are measurement deviations among different manufacturers' Bluetooth chips, no unified calibration standards and protocol specifications, and poor cross-platform compatibility [12].

Therefore, the application of Bluetooth positioning technology in complex indoor environment must be flexible and diversified.The integration with 5G can make use of the real-time data processing capability of inorganic edge computing and the layout positioning of Bluetooth to achieve meter-level positioning within 10 square kilometers in scenarios such as smart parks, and support tens of thousands of devices for concurrent operation [2].The combination with artificial intelligence can enhance the flexibility of the model, which not only reduces the calibration cost, but also improves the efficiency of data processing and positioning accuracy. Hardware should also usher in new breakthroughs. If the 60GHz band of millimeter-wave Bluetooth can be used, it can reduce the impact of multipath effect.The combination of quantum dot tag and Bluetooth communication technology can achieve nanoscale positioning accuracy, so that Bluetooth positioning can be extended to the application of positioning accuracy requirements.

7. Conclusion

In order to improve the accuracy of Bluetooth positioning in complex environments, this paper first analyzes the technical principles of RSSI, AoA/AoD, ToF and fingerprint positioning, and then concludes that three factors, such as environmental interference, hardware differences and algorithm limitations, have an impact on the positioning accuracy.By synthesizing research achievements from recent years, this study proposes practical precision enhancement strategies across three dimensions: hardware optimization for multi-antenna and signal enhancement, algorithm improvements in data fusion, machine learning, and filtering algorithms, as well as system design involving anchor point layout and dynamic calibration. The effectiveness of these strategies is validated through application cases in commercial, industrial, and medical fields.

Research shows that it is difficult for a single technology to meet the high precision requirements of complex environment, and the integration of multiple technologies and the iteration of intelligent algorithm are the inevitable trend.Research shows that it is difficult for a single technology to meet the high precision requirements of complex environment, and the integration of multiple technologies and the iteration of intelligent algorithm are the inevitable trend.

This study hopes to provide theoretical guidance for the engineering practice of indoor positioning technology, and relevant strategies can be directly applied to smart shopping malls, intelligent manufacturing, smart medical care and other scenarios, so as to promote the intelligent upgrading of indoor space management.With the reduction of hardware costs and the maturity of algorithms, Bluetooth positioning technology will play a core role in more intelligent scenarios, laying the foundation for the construction of efficient, safe and convenient indoor environment.

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