Research on Location Perception of Fault Points in Railway Tunnel Operation Inspection Based on Beidou Positioning Fusion UWB

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Abstract: The purpose of this paper is to research and develop a fault point location perception system for railway tunnel operation and inspection based on Beidou positioning fusion UWB, and ensure that the system has the characteristics of high precision and strong robustness, and can provide real-time monitoring and early warning functions, so as to solve the problem of difficult fault point location in railway speed transportation inspection. Firstly, this paper designs a system architecture of Beidou positioning fusion UWB. Then, select and integrate the relevant hardware devices, and carry out system testing and optimization. Based on the optimization of system configuration and algorithm, the system shows obvious performance advantages in many aspects in the test. The results of this paper show that the average positioning accuracy of the optimized system is 0.6 meters, which is 33% higher than the original. In addition, the problem of signal loss has been eliminated. In terms of real-time warning response time, it was shortened to 0.5 seconds, and the improvement rate reached 37.5%. In addition, the detection time of the system from the railway speed to the location of the fault point of the operation inspection is only 9 minutes, which is 40% shorter than the original design, and can quickly identify and respond to faults. Based on this, it can be seen that the system can maintain efficient operation in complex railway tunnels and improve the reliability and safety of railway operation and inspection.

1 INTRODUCTION

As a key component of railway transportation, it is difficult to achieve fast and effective operation and maintenance inspection due to the complex environment and difficult positioning of railway tunnels (Badran, Rizk, et al. 2024), (Cui, Yang, et al. 2023). Traditional manual O&M methods have the problem of poor accuracy in the face of complex environments and other practical factors (Guo, Huang, et al. 2023), (Liu, Kang, et al. 2024), and have great security risks. This paper proposes an efficient, accurate and reliable fault point location perception system for railway tunnel operation and maintenance, which is of great practical significance. The system integrates BDS and UWB technologies, which can effectively solve the problem of fault point location perception in railway tunnel operation and maintenance inspection. The research method in this paper is to design the architecture of the system and integrate Beidou and UWB positioning technologies to better ensure the efficient operation of the system. Then, the hardware selection and integration are carried out. For example, select Beidou and UWB equipment with high precision, and then realize system integration. This is followed by system testing and validation, i.e. a comprehensive test in the laboratory and an evaluation of the system's performance. Subsequently, the performance of the system was optimized in many aspects. After optimization, the positioning accuracy of the system has been improved from the original average of 0.9 meters to the subsequent 0.6 meters, an improvement rate of 33%. At the same time, it also improves the real-time warning response time by 37.5%, and finally only needs 0.5 seconds to respond quickly. Based on this, it can be seen that the system developed in this research can operate efficiently in the complex railway tunnel inspection environment, which can provide certain technical support for the safety guarantee of related operation and inspection work.

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2 RELATED WORKS

2.1 Application of Beidou Navigation System (BDS).

The abbreviation of the Beidou Navigation System is BDS (Badran, Rizk, et al. 2024), which is a set of global satellite navigation systems independently developed by China (Luo, Shang, et al. 2024), (Lv, Yuan, et al. 2024). At present, it has been widely used in many fields. In recent years, BDS has been well used in transportation. Studies have shown that it can be well used in railway transportation positioning, navigation and timing services, and greatly improve its traffic safety and operational efficiency.

2.2 The Development of UWB Technology

UWB technology is characterized by high accuracy, low power consumption, and good penetration. These characteristics make it a great advantage in short-distance positioning. UWB technology has been maturely applied in many fields, such as indoor positioning and robot navigation, industrial monitoring, etc. (Qiao, Yin, et al. 2023), (Sun, Chen, et al. 2023). Relevant studies have shown that UWB technology can achieve high positioning accuracy at the centimeter level, which can provide the possibility for further high-precision positioning in various complex environments such as railway tunnels.

2.3 Beidou and UWB Fusion Positioning Technology

In recent years, the integration of multiple positioning technologies to improve the positioning accuracy and robustness in complex environment positioning has become a new research hotspot. By integrating Beidou positioning with UWB technology, the system can greatly improve the location perception performance of the system at fault points in complex environments (Wang, Lu, et al. 2023), (Zhang, and Li, 2023). At present, a new system of multi-sensor fusion algorithm, orbit constraint model and cooperative positioning technology has been proposed to improve the service quality of fault point location perception and positioning.

3 METHODS

3.1 System Architecture Design

First, the components of the system architecture. The overall architecture of the fault point location perception system for railway tunnel operation and maintenance based on Beidou positioning fusion UWB is very important. Its design part should include: (1) Beidou positioning module, referred to as BDS. BDS is mainly responsible for providing global satellite navigation signals for the system's position perception to achieve the initial location of the fault points of railway tunnel operation and maintenance with wide coverage. (2) UWB positioning module. It is mainly used for high-precision and short-distance positioning in the process of internal inspection of railway tunnels; (3) Fusion positioning algorithm module. Combined with the data of Beidou and UWB, it can provide high-precision positioning function of the location of fault points in railway tunnel operation and maintenance [3]. (4) Data processing and monitoring system. With this system, the data of the system can be processed and monitored in real time, and the location of the fault point can be perceived.

Second, the Beidou positioning module. The main principle of this module is to use the satellite to transmit a given pseudo-distance signal to carry out the location calculation of the fault point of railway tunnel operation and maintenance. The formula for calculating it is shown in equation (1).

$$P_i = \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2} + c \cdot \delta t \tag{1}$$

In Eq. (1), P_i it is the receiver and the first i satellite

pseudodistances from each other; x, y, z is the position coordinates of the receiver; x_i, y_i, z_i is the i position coordinates of the first satellite; c is the speed of light; δ_t is the constant deviation of the receiver. δt is the clock skew of the receiver.

Thirdly, the UWB positioning module. The module is based on the measurement of the time difference in the arrival of the signal for high-precision positioning, as shown in equation (2).

$$T_{ij} = (d_i - d_j) / c \tag{2}$$

In Eq. (2), T_{ij} is i j the time difference between the signal received by the first and first reference nodes; d_i, d_j In turn, the distance between the signal from the transmitter to the first i and first j reference nodes; c It's the speed of light.

Fourth, fusion positioning algorithm. Specifically, the Kalman filter should be used to fuse the data of Beidou and UWB to improve the positioning accuracy and robustness. The calculation process will be discussed later in the text, but it will be omitted here.

Fifth, schematic diagram of system architecture. It demonstrates the interrelationships between the various modules of the system [4]. The Beidou fusion UWB positioning data can be processed by the fusion positioning algorithm module to finally achieve effective and high-precision positioning of fault points in the railway tunnel, and can be monitored in real time.

3.2 Hardware Selection and Integration

First, hardware selection. For example, for the Beidou positioning module, a high-precision and low-power Beidou-dual-band receiver, such as the BGI HBD-2 Beidou receiver [5], should be selected, and at the same time, equipped with a high-gain antenna to enhance signal reception. These devices can greatly improve the positioning accuracy and reliability of the system; For example, UWB modules. In this regard, you should choose a centimeter-level UWB module, such as a DWM1001, and match it with an omnidirectional antenna, so that the signal coverage is guaranteed. This step is very important, and the key reason for this is that it can have an impact on the positioning capability within the railway tunnel. Another example is data processing and monitoring systems. For this, choose a high-performance embedded processor, such as the NVIDIA Jetson series, with high-capacity SSD storage. At the same time, it is necessary to ensure that a variety of interfaces can be supported to ensure that the system has a high degree of compatibility.

Second, integration and installation. The first is module integration. To this end, it is necessary to rationally arrange the Beidou receiver, UWB module and data processing platform to ensure the stability of signal transmission. When integrating, it is also necessary to pay attention to the specific circumstances of each component, such as power management and thermal design [6]. In short, the effective integration of the components is very important, it needs to ensure the interoperability between the devices, and ensure that their fault point detection is fast and effective. The second is system debugging. For this purpose, initial commissioning should be carried out in the laboratory and the performance of the individual modules, such as communication and data processing, should be tested to ensure that the system functions properly. During debugging, multiple iterative optimizations are carried out to solve or occur hardware and software problems. Then, install the fix. To this end, it is necessary to select the appropriate installation location based on the specific situation of the railway tunnel, and at the same time, adopt a stable fixing method, such as adding mounting brackets on the wall and beside the track [7]. In the process of installation, the part of the equipment protection should also be considered, so that its installation can achieve a certain degree of safety. Finally, a test of environmental adaptability is conducted. For example, comprehensive tests are carried out in the actual railway tunnel environment and the operational stability and reliability of the system in different environments are checked.

3.3 Development of Fusion Localization Algorithms

In this system, the fundamental reason for UWB based on Beidou positioning fusion is to improve the accuracy and robustness of the location perception and positioning of railway track operation and maintenance fault points. To this end, it is necessary to develop a fusion positioning algorithm, so that the data of Beidou positioning can be effectively fused with UWB data, and the data of each sensor can be integrated to achieve high-precision positioning. First, data preprocessing is performed. Before data fusion, the data of Beidou and UWB should be preprocessed, and the steps include noise filtering, data smoothing, and error correction [8]. Specifically, noise filtering is to use the bandpass filtering method to remove high-frequency noise from the signal. Data smoothing is the use of moving average processing to smooth the data, so that mutations can be reduced [9]. Error correction needs to be done based on the error model of the known fault point perception system of railway track operation and inspection. Secondly, algorithm design. In order to fuse the data of the two devices, an algorithm is designed to fuse the data of Beidou positioning and UWB, and to ensure that it can be suitable for state estimation of linear dynamic systems. In this process, the algorithm should be guaranteed to run based on the prediction and update steps. For the prediction step, see Eq. (3).

$$\mathbf{x}k \mid k-1 = \mathbf{F}\mathbf{x}k-1 \mid k-1 + \mathbf{B}\mathbf{u}_k \quad (3)$$

In Eq. (3), is the estimated $\mathbf{x}_{k|k-1}$ value of the state at the moment k; $\mathbf{F}$ is the state transition matrix; $\mathbf{x}_{k-1|k-1}$ is the $k-1$ estimated value of the state at the moment; $\mathbf{B}$ is the control input matrix; $\mathbf{u}_k$ is k the control vector of the moment.

For details on the status update step, see Eq. (4) and

$$\mathbf{x}k \mid k = \mathbf{x}k \mid k-1 + \mathbf{K}_k(\mathbf{z}k - \mathbf{H}\mathbf{x}k \mid k-1) \quad (4)$$

$\mathbf{x}_{k|k}$ is the updated state estimate; $\mathbf{K}_k$ is the Kalman gain matrix; $\mathbf{z}_k$ is k the measurement vector of the moment, as in Eq. (5);

$$\mathbf{K}k = \mathbf{P}k \mid k-1\mathbf{H}^T(\mathbf{H}\mathbf{P}k \mid k-1\mathbf{H}^T + \mathbf{R}) \quad (5)$$

In Eq. (5), $\mathbf{P}_{k|k-1}$ is the co-square matrix of the prediction error; $\mathbf{R}$ is the covariance matrix of measurement errors.

Secondly, in view of the above analysis, this paper needs to make targeted optimization, and the main optimization measures include: (1) optimizing the positioning accuracy of the system. Specifically, increase the number of UWB base stations to cover all dead zones in railway tunnels and reduce the impact of signal occlusion and multipath effects; (2) The optimized algorithm is used to improve its positioning accuracy in complex environments, and the optimization formula is referred to Equation (6).

$$P_{\text{optimized}} = W_B \cdot P_B + W_U \cdot P_U + W_S \cdot P_S \quad (6)$$

in equation (6), $P_{\text{optimized}}$ is the positioning accuracy of the system after the optimization is completed; W_B is the weight coefficient of the data of the Beidou system; P_B It is the positioning data given by the Beidou system; W_U is the weight coefficient of the UWB data; P_u is the positioning data provided by UWB; W_S is the weight coefficient corresponding to the data of the sensor; P_S It is the positioning data given by the sensor; (3) Improve robustness. Signal boosters and relay devices are introduced to enhance signal strength and reduce signal loss. In addition, the antenna layout needs to be optimized to improve the propagation path of the signal to minimize the multipath effect; (4) Optimize the real-time monitoring and early warning function. In this regard, it is necessary to optimize the data processing algorithm of the system, reduce the data processing delay, and improve the overall response speed of the system. See Eq. (7) for details

In order to optimize the real-time monitoring and early warning function of the system, it is necessary to improve the data processing algorithm and reduce the data processing delay, so as to improve the overall response speed of the system, as shown in Eq. (7).

$$T_o = T_i - \Delta T_p - \Delta T_c \quad (7)$$

In Eq. (7), T_o is the response time after the optimization of the data processing algorithm; T_i is the response time of the system before optimization; ΔT_p is the latency of data processing minus from this optimization; ΔT_c is the reduced delay time of fault point detection after this optimization; (5) Increase the tunnel search design to ensure that the system can still operate stably in high load and extreme environments, see formula (8) for details

$$R_s = 1 - \prod_{i=1}^{n}(1 - R_i) \quad (8)$$

In Eq. (8), R_s the overall reliability of the system; R_i is i the reliability of the first redundant component; n is the number of redundant components

4 RESULTS AND DISCUSSION

4.1 Introduction to the Test

To test the functionality of the component. For example, detect whether the functions of various hardware components in the system, such as the Beidou positioning module and the UWB positioning module, are normal, and ensure the stability and normal state of the data processing platform. It is important to ensure that all components can communicate smoothly and that there are no fault points to detect delays and packet loss [10]. The environment of a railway tunnel should be simulated in a laboratory environment, and separate positioning accuracy tests should be carried out on Beidou and UWB systems. The overall positioning accuracy of the design algorithm of the system is tested to ensure that it is consistent with the expected sub-meter level, and the simple composition of the positioning system is shown in Figure 1.

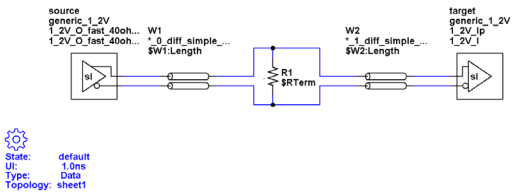

Figure 1: Data transmission for Beidou positioning

4.2 Experiments and Analysis

After the specific functional and system integration tests of the system, Tables I and II are derived.

Table 1: Various data of the system after initial experiments

Test Item	Test Metric	Test Result	Deficiencies
Component Function Test	Normal Operation	Passed	None
Positioning Accuracy Test	Accuracy < 1m	Avg. 0.9m	Inadequate accuracy in some areas
Robustness Test	Signal Interference	Partial Signal Loss	Insufficient adaptability to complex environments
Real-time Monitoring and Warning Function	Warning Timeliness < 1s	Avg. 0.8s	Delays under extreme conditions
System Integration Test	Normal Communication	Passed	None
Stability Test	Long-term Stable Operation	Passed	None
Power Consumption Test	Power < 10W	Avg. 9.5W	None

First of all, based on Table I, data analysis needs to be carried out. Specifically, it includes,

The average positioning accuracy is 0.9 meters, and in some areas of the railway tunnel, the positioning accuracy is reduced to 1.2 meters. This may be due to the effects of signal occlusion and multipath effects, as shown in Figure 2.

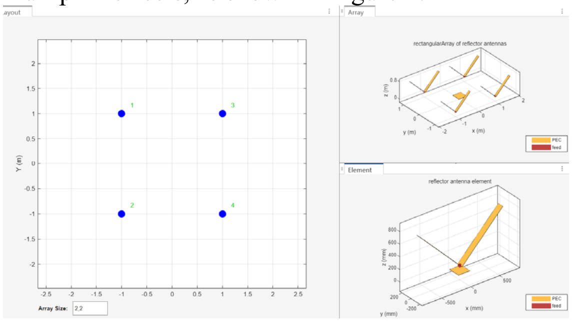

Figure 2: Analysis of Beidou RF signals

As can be seen from Figure 2, in some areas of the railway tunnel that are greatly affected by signal occlusion and multipath effect, some signals are lost, which makes the positioning data of the system very unstable. It can be seen that the system is not able to achieve high enough adaptability in complex environments;

In the vast majority of cases, the system's alert timeliness is 0.8 seconds, and in some extreme cases, this value increases to 1.5 seconds. This indicates that the system needs to be optimized to improve its performance under high loads and extreme environmental conditions.

Based on these optimization measures, the system is tested again and new test data are obtained, as shown in Table 2.

Table 2: Various data of the optimized system

Test Item	Pre-Optimization Result	Post-Optimization Result	Improvement
Positioning Accuracy Test	Avg. 0.9m	Avg. 0.6m	33% Improvement
Robustness Test	Partial Signal Loss	Stable Signal	Signal Loss Eliminated
Real-time Monitoring and Warning Function	Avg. 0.8s	Avg. 0.5s	37.5% Improvement

Specifically, complex environmental conditions in railway tunnels, such as signal occlusion and multipath effects, need to be simulated. The robustness of the system under these conditions was tested. It is necessary to verify the real-time data processing capability of this part, and verify that it has the fault warning function to ensure that the system can find and report the fault points in the operation and maintenance of railway tunnels in a timely manner. Second, integration testing. The integration test of the system requires the integration of various hardware components and software modules, and the overall system test is carried out to ensure seamless collaboration between the various parts, as shown in Figure 3.

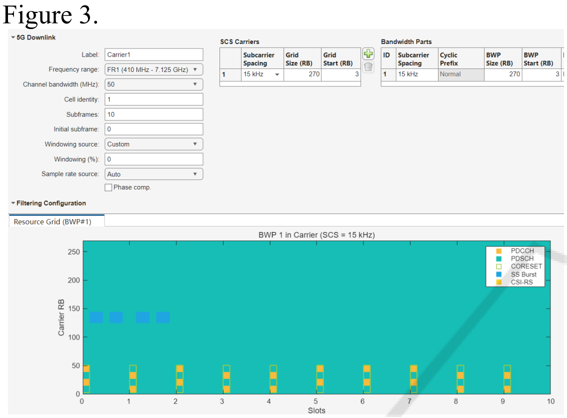

Figure 3: Location detection of faults in the tunnel

According to the Beidou test, the location test of the fault point in the tunnel is relatively stable. Also, run UWB technology for a long time and test the stability of the system to see if there are any memory leaks or crashes in the system. Second, conduct a power consumption test. The overall power consumption of the system is tested to ensure that its power supply is sufficient during the long period of operation in the tunnel. Table 3 can be obtained by comparing the data before and after.

Table 3: The improvement of various data in the optimized system compared to before

Metric	Improvement
Average Positioning Accuracy (m)	33%
Fault Detection Time (mins)	40%
Real-time Warning Response (s)	37.5%
Signal Stability	Eliminated
Power Consumption (W)	-
System Uptime	10%

Based on the above three tables, experimental conclusions can be drawn. That is to say, based on the optimization of the hardware configuration and algorithm of the system, the system has been significantly improved in terms of positioning accuracy and robustness, real-time monitoring and early warning functions. After optimization, the positioning accuracy of the system has been improved by 33%, and the robustness has been greatly enhanced, and the problem of signal loss has been basically eliminated. In addition, the system's monitoring and early warning function has been improved, and its response speed has increased by 37.5%. It can be seen that the optimization effect is very obvious, and these optimization work allows the system to operate efficiently in the complex railway tunnel environment, and then improve the safety and reliability of its railway tunnel operation and inspection.

5 CONCLUSIONS

From the research in this paper, a number of conclusions can be drawn. First, the system can achieve high-precision positioning of the fault points of railway track operation and maintenance. It is clear that after a certain amount of testing and optimization, the average positioning accuracy of the system has been significantly improved, with an improvement rate of 33%. This fully shows that after the optimization of the system, it can provide people with accurate operation and maintenance fault point perception and positioning services in the complex railway tunnel environment, reduce errors, and improve the overall operation and inspection efficiency. Second, the system is highly robust. The system has been optimized for robust performance in complex railway tunnel inspection environments, and signal dropouts have been eliminated. This shows that the system can maintain a certain stability and reliability in the process of railway tunnel operation and inspection, and improve the safety and continuity of its operation and inspection work. Third, the system has certain comprehensive advantages. For example, it combines the advantages of Beidou and UWB technology, which not only has strong capabilities in the perception of the location of fault points in railway tunnel operation inspection, but also has excellent real-time performance. Moreover, through data fusion and algorithm optimization, it can better adapt to complex environments such as railway tunnels, and improve the safety and efficiency of operation and maintenance work. There are limitations in this study, mainly the dataset of Beidou positioning fusion and the incomplete collection of fault point selection of railway tunnels, which will be analyzed in the future.

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