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Tunnel Health Monitoring System Based on Wireless Sensor Network

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Abstract: At present, China is not only the country with the most highway tunnels, but also the country with the longest railway tunnels, but with the increase of tunnel use time, its structure is gradually aging, resulting in arch settlement, segment damage, misplacement, and leakage a series of problems; in order to solve these problems, regular monitoring and maintenance of the tunnel is needed, because manual monitoring and maintenance of the tunnel during the operation is very inconvenient. Based on the above background, the purpose of this paper is to study the tunnel health monitoring system based on wireless sensor networks. First, this article uses a modular approach to develop the system hardware platform, focusing on the design of the ZigBee wireless communication unit, power management unit, flash data storage unit, clock unit, etc.; then, in order to ensure the reliability of the sensor data, design correction error detection and detection algorithms are embedded in the underlying nodes to reduce errors in the storage and transmission of data. At the same time, for the interference of sensor data during acquisition, wavelet denoising is used to preprocess the data, and a random forest algorithm is used to establish the tunnel health monitoring and evaluation system analyzes and evaluates the tunnel status information. Finally, experimental verification is performed. The experimental results show that the wireless sensor data loss rate is 9% when a train passes, and the wireless sensor data loss rate is only 3% when no train passes. By optimizing the node arrangement and ad hoc network, the reliability of data transmission can be improved.

1. Introduction

China's economic development is still in a period of rapid growth, and infrastructure construction is an important guarantee and foundation for economic development; and with the rapid economic growth of our country, the urban population has increased sharply and the population flow has intensified. Transportation, environment, resources, etc. have brought great pressure. At the same time, due to the backward economic development in remote and mountainous areas, the difficulty of road construction on the mountain has brought great resistance to the economic development of these areas, and it is also not good for these areas. Development and utilization of natural resources. The tunnel construction is already one of the important infrastructure constructions in China. It can fully utilize and develop China's land resources. The construction of tunnels such as urban subways, highway tunnels, and railway tunnels will greatly improve the traffic and other aspects of these areas. China is not only the country with the most highway tunnels, but also the country with the longest railway tunnels. After the completion of the tunnel, the tunnel-shaped complex surrounding rock structure is often caused by the great differences in the technical level, surrounding rocks and environmental conditions of the construction unit when the excavation steps, anchor shotcrete support and the construction of the molded concrete are carried out during the construction process. As the service time of the tunnel increases, a series of problems such as settlement of the vault, broken segments, misplacement, and leakage of water appear. A series of problems such as the need to regularly monitor and maintain the tunnel will accelerate the aging of the tunnel. Reduced service life, but manual monitoring and maintenance during the operation of the tunnel is very inconvenient; especially for subway tunnels, manual monitoring is very dangerous due to the excessive speed and high frequency of subway trains. It would be a waste of resources and affect traffic if it was just for monitoring. In recent years, with the rapid development of sensor technology, information acquisition technology and test analysis technology, real-time and continuous structural health monitoring systems based on various monitoring methods have been competing in the field of civil engineering, and it is widely used in engineering fields such as bridge and water conservancy.

Due to the importance of tunnel health research, many research teams have started researching tunnel health and achieved good results. For example, Jay proposed a new method for remote detection using a vehicle ground penetrating radar. It consists of 6 channels. The distance from the aerial antenna to the side wall is about 0.93m, about 1.5m, and the distance to the vault is about 1.7m, about 2.25m. The scanning rate of each channel is 976 times / second. When the sampling point interval is 5CNI, the maximum test speed can reach 175kM / HR. With this speed and aerial transmitting antenna, the system has great advantages over existing methods. In other words, electrified railways do not require power outages and do not require time for maintenance. In fact, they will not interrupt the normal operation of the railway. The system has been run on the Baoji-Zhongwei, Xiangfan-Chongqing railway, and has achieved good test results [1-2]. Yong proposed a new high-precision temperature measurement system to avoid false detection in the tunnel. This system was developed and implemented on the basis of a platinum thermistor and a constant current source excitation circuit, which is designed to convert temperature signals into electrical signals. The real-time temperature monitoring system and data acquisition are automatically controlled by the embedded device S3C6410 microprocessor. Obtain the measured values from the voltage parameters, and then process and analyze these data on the host computer software. By analyzing the data of accuracy and error, the accuracy of the system is obtained, which is obviously higher than ± 0.05 °C. Modeling and experimental results show that this method can monitor and locate the frost damage of different tunnel linings online with high accuracy [3-4]. Although the research results are richer now, there are still some shortcomings, mainly due to the insufficient comprehensive monitoring data of the tunnel.

In the research of wireless sensor networks, Zigbee is a good method that can solve many monitoring problems. Therefore, it is widely used in sensor monitoring research. Tareq introduced a low power consumption for remote monitoring of quality environment. Design, development and construction of sensor nodes. The system was developed at INICTEL-UNI as part of the project "Peru Natural Resources and Environmental Monitoring Telemetry System". The sensor node is realized by the development iterative increment method, and the construction of three electronic boards is considered. Each electronic board works as an independent module with specific functions. The sensor node can transmit data through GPRS (General Packet Radio Service) or ZigBee. In addition, the acquisition and transmission of the readings obtained by the sensor nodes is done through a low-power microcontroller with a power-saving control system that allows greater operational autonomy. The data is sent to the Web server on the Internet through the ZigBee gateway GPRS or GPRS module [5-6]. Due to the effectiveness of the ZigBee method, can the ZigBee method be applied to tunnel health monitoring to solve the problem of insufficient monitoring data.

This paper researches and develops a wireless sensor device that integrates the deformation monitoring of the ballast road and the environmental monitoring in the tunnel. The deformation of the tunnel can be reflected in real time by monitoring the stress changes of the lining of the tunnel, and the temperature and humidity in the tunnel are detected. The topology of the ZigBee tree network is used to build a wireless sensor network in the tunnel, and the data measured by each sensor is transmitted to the host computer for processing, display and alarm. Aiming at the problems of large volume of monitoring sensors and complicated installation environment of monitoring equipment in engineering monitoring projects, the application of wireless sensor network technology (WSN) to the automated safety monitoring of building structures, combined with the data communication characteristics of safety monitoring systems starting from the two aspects of wireless communication networking and low-power supply strategy, a communication protocol suitable for tunnel safety monitoring terminal equipment was developed, and the sensor monitoring data collection and control were realized, eliminating the need for sensor terminal deployment power supply at the project site. The workload of power and communication cables saves cable costs while improving work installation efficiency.

2. Proposed Method

2.1. Wireless Sensor Network Embodiment Structure

The typical structure of a wireless sensor network is composed of 4 parts, namely a sensor node (SN), a sink node (SN), a gateway node and a management base station (with a terminal computer system) [7]. As shown in Figure 1. The area sensor transmits the detected data information through a wireless channel. When the distance is short, it can be directly transmitted to the sink node or relayed by a nearby node at a long distance. The sink node can achieve the initial integration of the information and send the processed information to the gateway. The gateway generally has a very good long-distance communication module, which can realize the remote transmission of data, and finally the relevant information is received by the monitoring station [8-9].

The sensor node is a micro-embedded system at the monitoring site. It has the capabilities of data sensing, information storage, and communication transmission of general embedded micro-systems [10]. The new sensor node not only has the terminal collection function, but also can play the role of routing and transmission itself, realize information interaction with other nodes, half-way forwarding, management and preliminary integration, etc., and can be adjusted according to the control instructions issued by the higher-level equipment [11].

The sink node is the medium that initially manages the terminal nodes. After receiving the terminal node's information transmission, it will classify and identify the information [12]. For long-distance communication, the corresponding transceiver module is used to realize the wireless transmission and reception of data. The information is mainly transmitted to nearby gateway nodes for further forwarding and processing of the data [13-14].

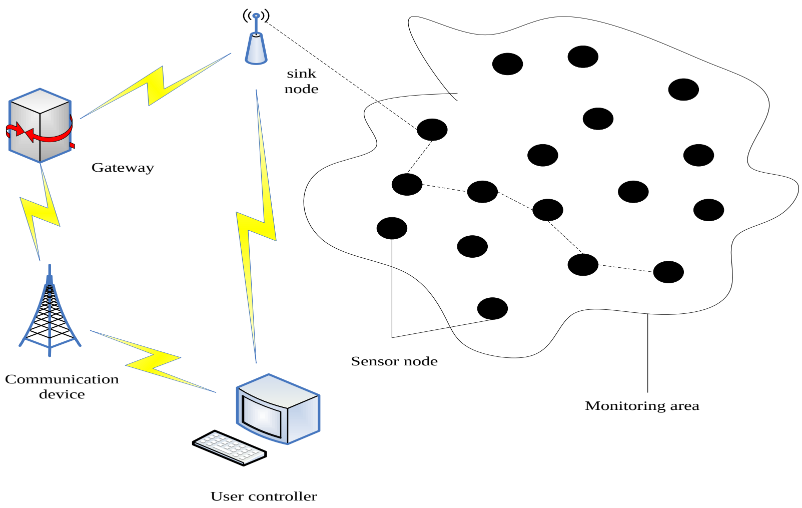

Figure 1. Wireless sensor network architecture

The gateway node has strong information processing, storage and communication capabilities. Generally, gateway nodes need to work continuously for a long time and receive a large number of data transmission tasks, so they are often equipped with relatively stable energy devices in the design. The gateway node can realize wireless transmission of data or wired connection to the network. The two communication protocol stacks can achieve a good conversion at the gateway node, which has good selectivity and convenience for actual project development.

Compared with current wired sensor networks, wireless sensor networks have their own unique advantages, mainly in the following aspects:

1) Easy to install: On-site wiring in traditional wired information collection networks is difficult and difficult to work. It is often necessary to dig trenches for wiring. It is very difficult to connect to the network, and the cost of wiring required for wiring is high, and workers wiring the cost of construction plus the cost of a large number of cables greatly increases the cost of the entire system, while the wireless sensor network does not need to arrange communication lines, and the installation is more convenient and flexible, which greatly saves the cost caused by wiring [15].

2) Flexible deployment: Compared with wired sensor networks, wireless sensor networks are free from the constraints of communication cables. Sensor nodes can be moved and arranged at will in the sensing area, and various topological structures can be formed freely to facilitate the movement and expansion of nodes. It is easy to meet the needs of continuous addition and deletion of later nodes.

3) Convenient maintenance: The maintenance of nodes in the middle and later stages of the wired sensor network involves a large number of communication cables, which is quite troublesome to maintain. In wireless sensor networks, target nodes do not involve communication lines, which makes maintenance easier.

4) Flexible networking: The general communication network of the wired sensor network uses the bus method to communicate. The networking method is fixed and single, and the wireless sensor network can achieve flexible and changeable networking through various networking algorithms. Algorithm to achieve more efficient and diverse networking methods.

5) Simple power supply: The power supply method of wired sensor network generally uses power supply cables for power supply, while the wireless sensor network generally uses batteries or solar panels to supply power, no power cord is needed, and power supply is simpler and more convenient [16-17].

2.2. Wireless Network Communication Technology

A variety of communication technologies are used in wireless sensor networks, which are mainly divided into "short-range wireless communication methods" and "long-distance wireless communication methods". Wifi, Zigbee, Bluetooth, etc. are common in short-range wireless communication technology, and large-scale satellite communication towers are representative of long-distance communication methods.

Wireless communication technology has many unique advantages. Avoiding the laying of complicated lines and the establishment of physical lines can greatly reduce the cost of investment. The wireless communication is extremely scalable, not easily limited by industrial environmental conditions, the communication method is flexible, and it is easy to analyze the fault conditions in communication. [18]. This project mainly uses short-range wireless communication technology. A simple comparison of common short-range wireless communication technologies from multiple aspects is shown in Table 1.

Table 1. Multiple wireless communication methods

Technology	RFID	Wifi	Bluetooth	UWB	Zigbee
Cost	Lower	Higher	Lower	Highest	Highest
Power cycle	Several years	A few days	A few days	Hours	Several years
Targeting	Region	Region	Region	Region	Region
Communication distance	100m	100m	100m	100m	100m
Communication speed	Extremely fast	6.75Mb/s	6.75Mb/s	100Mb/s	250/20/40kb/s
Working frequency	1-100GHz	2.4GHz	2.4GHz	3.1-10.6GHz	2.4/868/915GHz

The table above makes a comparison of several common communication technologies in wireless sensor networks. There are advantages and disadvantages in different aspects.

RFID (radio frequency identification technology) is a technology developed using the principle of electromagnetic space coupling. Non-contact changes in the spatial magnetic field will generate specific information for transmission, and use electronic devices to detect, track, and respond [19-20]. This technology is currently widely used in access control systems such as libraries and shopping malls.

Wi-Fi technology is a wireless local area network technology developed based on the 802.11 protocol. Its effective coverage area can reach about 100 meters, with a wide range and a fast data transmission rate. At present, Wi-Fi has been popular in mobile vehicles such as high-speed rail [21-22].

Ultra-wideband (UWB) technology mainly uses nano-scale pulses for data communication, and has a wide transmission frequency band, high speed, and strong information confidentiality. The characteristics of nano-scale pulse wave can penetrate the wall in a small range, and it is successfully applied to penetrating radar [23].

Zigbee technology is a short-range, low-complexity, low-power, low-speed, low-cost, two-way wireless communication technology based on the IEEE802.15.4 standard, which complies with the IEEE802.15.4 standard area network protocol. This technology has been successfully applied in the fields of home and building control, agricultural information collection and control [24-25].

This subject is based on actual needs and environmental analysis, comparing multiple wireless communication technologies, taking into account factors such as system cost, deployment environment, and signal characteristics. Using Zigbee technology as the subject's communication subject has great advantages in cost budget and actual communication quality. At the same time, the use of Zigbee communication can reduce the research on related technologies in the subject. For example, the random channel access technology (csma-ca) in the Mac layer of the Zigbee protocol stack is mature and can be directly ported to the protocol stack. The high security encryption algorithm in Zigbee communication can guarantee the security of data transmission can be easily realized by grouping the network nodes through software settings in the Zigbee protocol stack.

(1) Zigbee technical characteristics

ZigBee is a short-range, low-power, low-data-rate, low-complexity, and low-cost two-way wireless communication technology. It mainly has the following characteristics:

1) Low power consumption. This is the most prominent advantage of ZigBee compared to other wireless sensor networks. ZigBee can work normally for 6 months to two years using ordinary 2 AA batteries in low power consumption mode. This has great advantages in areas where maintenance is not easy.

2) Low cost. Compared with the expensive price of existing remote network equipment, the cost of ZigBee wireless sensor network nodes is very low, and there is no patent fee for ZigBee protocol. With the mass production of existing ZigBee chips, the price is still further reduced.

3) Low data transmission rate. The data transmission rate of ZigBee is 20-250kbps. Provides 250kbps (2.4GHz), 40kbps (915MHz) and 20kbps (868MHz) transmission rates.

4) Short delay. The device search delay is typically 30rns. It only takes 15rns from the sleep state to the working state, and the node network delay is 15ms. It is applicable to the field of wireless control where the delay is relatively poetic.

5) Large network capacity. The star topology can accommodate 1 master and up to 254 slaves; the mesh topology can support a maximum of 65,000 nodes.

6) Security. ZigBee uses the common AES-128 encryption algorithm, which provides data integrity check and authentication functions.

7) Reliable. ZigBee's collision avoidance mechanism can effectively avoid competition and conflicts during data transmission. The nodes in the network are automatically and dynamically networked, and information is transmitted in the network through automatic routing, which ensures the maximum security and reliability of information transmission.

(2) Zigbee mesh topology

Zigbee network mainly adopts 3 kinds of topologies: star, tree and mesh, which are suitable for different applications. When making network selection, the differences in topology cause differences in the configuration of network nodes. Based on the sensor network, research the existing topology control technology and optimize the existing algorithm, design a cluster-head multi-hop topology control algorithm based on geographical location, and design a topology control system based on B / S structure to show the final Topology.

The mesh topology is flexible and includes Coordinator, Router (multiple) and End Device (multiple). In theory, Router can also communicate with each other. This mechanism improves the information communication efficiency of the network and enhances the robustness of the structure to a certain extent. The mesh topology is shown in Figure 2.

The mesh topology can be optimized on the information transmission path. Thanks to the route discovery support function provided by the network layer, the development of the application layer does not need to consider the situation of the application layer.

The mesh topology has powerful functions. The network can communicate in a "multi-hop" manner. In theory, it can form an extremely complex network structure with the largest number of nodes. In the routing approach, it also has certain functions such as self-reorganization, routing maintenance, etc. It is especially suitable for multi-point close-range applications like the tree structure.

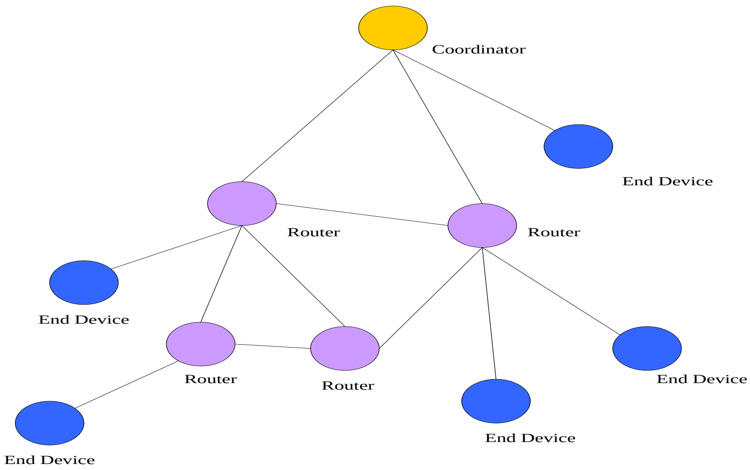

Figure 2. Mesh topology

2.3. Health Monitoring System

Tunnel structural health monitoring technology involves many disciplines (such as tunnel engineering, monitoring technology, data analysis and processing technology) and interdisciplinary comprehensive system engineering, which reflects the level of tunnel construction, management and maintenance in a country. According to the basic definition of the structural health monitoring system for civil engineering, combined with the characteristics of the tunnel engineering itself, the Tunnel Structural Health Monitoring System (TSHMS) is defined as follows: Sensing equipment, based on information collection data, network transmission technology, data analysis and processing technology, and computer technology, to form a tunnel health monitoring network to achieve real-time, long-term monitoring of tunnel structure-surrounding rock forces and deformation characteristics. Engineering experience, as well as the requirements of the code to establish a safety evaluation and early warning system for the tunnel structure, based on on-site monitoring data, combined with theoretical calculation and analysis, evaluate the overall safety status and service performance of the tunnel, and provide timely warning of possible dangerous situations, and guide the operation and maintenance part to configure maintenance resources. The wireless sensor network-based tunnel health monitoring system consists of wireless sensor nodes, wireless network transmission systems, data processing and control systems, and security assessment systems.

3. Experiments

3.1. Experimental Data Collection

The pressure change in the danger track is monitored by the pressure sensor to reflect the deformation degree of the danger track in real time, and the temperature and humidity sensors are used to detect the temperature and humidity in the danger track. The networking scheme uses the topology of the ZigBee tree network. The coordinator is responsible for establishing the network and uploading the data collected by the terminal nodes to the host computer monitoring software through the serial port; the router is responsible for the network expansion and data forwarding; terminal device nodes responsible for collecting monitoring data, including real-time data from pressure sensors, temperature sensors, and humidity sensors. In this way, a wireless sensor network in the danger lane is constructed, and the data measured by each node is transmitted to a host computer for processing, display, and alarm.

This design uses a ZigBee tree network topology. The network consists of a coordinator, several routers, and Ruoqi terminal equipment. The coordinator node is connected to the monitoring host through the serial port; the router is responsible for expanding the network; the terminal equipment is distributed on the site, and is responsible for gathering the stress, temperature, and humidity data on the site and transmitting the data to the nearest router. The data is forwarded to the coordinator via the router, and the coordinator is connected to the upper computer through the RS232 interface, and the data is transmitted to the upper computer for display.

3.2. Experimental Terminal Equipment Node Function Design

Functional design of the terminal equipment node. The terminal equipment node is composed of a core processing and communication unit, a stress monitoring module, a temperature monitoring module, a humidity detection module, and an alarm module. The core processing chip uses TI's CC2530 chip; stress monitoring uses bridge strain sensors and operational amplifiers as the main components to complete; the temperature monitoring module selects the temperature sensing chip DS18B20; SHT11 is responsible for humidity monitoring; the alarm module is composed of LEDs and buzzers sound and light alarm design. The functions to be implemented by terminal equipment nodes are as follows:

1) On-site stress, temperature and humidity monitoring;

2) Join the ZigBee network;

3) Data processing and transmission. CC2530 is responsible for processing the data collected by the sensor module and sending the processed data to the coordinator.

4) Alarm function. When one of the stress value, temperature value and humidity value exceeds the set threshold, the audible and visual alarm is activated.

5) Parameter setting function. Can set stress alarm, temperature alarm and humidity alarm threshold.

6) Timer sleep function. In order to ensure the low power consumption of the system, the sleep period of the terminal node can be set according to the actual needs.

3.3. Experimental Coordinator Functional Design

The coordinator is the core of the entire network and is responsible for the establishment and maintenance of the ZigBee network. On the one hand, it receives the data transmitted from the terminal device, and on the other hand, it forwards the data to the upper computer for display after processing. The coordinator needs to implement the following functions:

1) Establish a ZigBee network and assign a network address to the newly joined nodes.

2) Data receiving and processing functions. Receive the data transmitted by the terminal equipment node and process it.

3) Communicate with the host computer software. The coordinator communicates with the host computer software through a standard RS232 interface, transmits data to the host computer, and receives control commands from the host computer.

4. Discussion

4.1. Test Verification and Analysis of Tunnel Health Monitoring System Based on ZigBee Network

When the monitoring center node receives the remote server command or the acquisition service is triggered regularly, the monitoring terminal nodes in the monitoring area of the project are uniformly dispatched, and the functional instructions are sent to each monitoring terminal node one by one. The wireless communication network first establishes a communication link between the terminal node and the wireless center node, and formulates a communication protocol according to the working characteristics of the tunnel sensor to achieve one-to-many control between the wireless center node and the monitoring node.

In order to facilitate the communication between the monitoring center node and the monitoring terminal node, a communication protocol suitable for one-to-many sensor local area networking of the tunnel safety monitoring system was developed, realize the coding, decoding and subsequent function expansion of the communication command frame between the monitoring terminal node and the monitoring center node. The communication protocol uses a command response mechanism. After the central node sends a measurement command, the monitoring node returns a response data frame. Among them, the start character occupies 1 byte, which indicates the start of data transmission or reception. This article uses the start character as ":"; the address code occupies 4 bytes, of which the first two digits are the device address code and the last two digits are the device code. In a local communication network, the address code is unique; the command word occupies 2 bytes, of which command words 1-20 are general function codes; 21-99 are dedicated function codes; data bits occupy different numbers of bytes according to different commands ; The check code occupies 2 bytes, and the checksum is used for verification; the terminator occupies 2 bytes, and the system uses 0x0D0A as the end character. In addition, according to the working characteristics and functional requirements of the monitoring sensor, this article has developed a general function code suitable for wireless low-power monitoring sensor terminals, as shown in Table 2.

Table 2. Common function codes for wireless sensor network monitoring sensor terminals

Function code	Corresponding function	Remark
01	Query slave address	Multiple devices use time-delay response address encoding
02	Set the slave address	
03	Date setting	
04	Date query	
05	Control module power on	
06	Control module reset	
07	Control module is powered off	
08	Status query	
09	Work mode query	
10	Heartbeat package settings	Including heartbeat packet content, transmission cycle
11	Data query	Recent data query

In order to verify the actual performance of the ZigBee-based tunnel monitoring system, laboratory calibration tests and outdoor actual tunnel test tests were performed. The indoor calibration test mainly verifies the performance of the system, and the outdoor test mainly verifies the stability and reliability of the system in actual application scenarios, and tests its actual application performance.

MEMS three-axis sensor has an independent chip structure, its power supply is + 3.3V, and the measurement range is: ± 6.0g. In terms of sensitivity and stability, MEMS sensors have good characteristics. Although the accuracy is lower than that of force-balanced sensors and piezoelectric sensors, they have the advantages of miniaturization and price, and can be applied in situations where accuracy is not high. On a single-axis shaker, a high-precision force-balanced sensor comparison calibration test is used to verify its performance and correct the output acceleration data.

The shaking table test is mainly divided into three groups. The nodes of the tunnel structural health monitoring system and the force balance acceleration sensor are fixed on the shaking table, and the acceleration signals in the three directions of X, Y, and Z are calibrated and monitored. The shaking table test scene is shown in Figure 3.

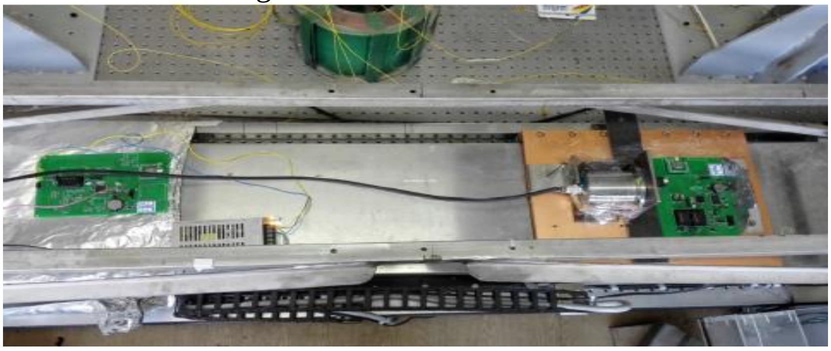

Figure 3. Shaking table test scene

The test process is to start the system to collect data, and then give the shaker a 1Hz sinusoidal excitation signal to make the shaker vibrate periodically. The sampling frequency of the system is 90Hz, and the collection frequency of the force balance sensor is 55Hz. The design vibration time of the shaking table is 90s. After the data is obtained, the data is analyzed in time and frequency domain using MATLAB software, and the calibration curve is drawn by comparing the data. The time-domain diagram of the x-axis acceleration of the MEMS sensor is shown in Figure 4.

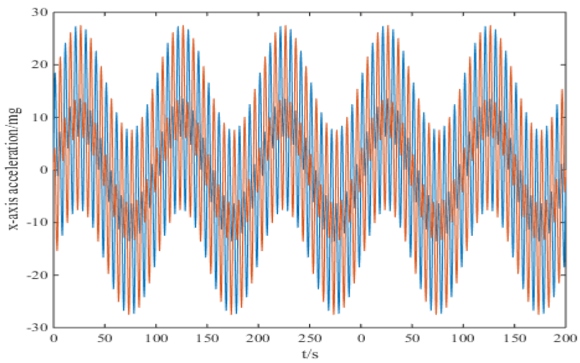

Figure 4. MEMS sensor x-axis time domain signal plot

From Figure 4, it can be seen that the x-axis time domain diagram of the force balance sensor and the MEMS acceleration sensor are basically the same, but because the accuracy and anti-interference ability of the MEMS sensor is worse than the force balance sensor, it can be seen that the noise in the frequency spectrum of the signal collected by the MEMS sensor is more obvious. In order to calibrate the sensor data more accurately, a section is taken from the stable time domain signals of the two sensors for data comparison and calibration.

The test process is to start the system to collect data, and then give the shaker a 1Hz vibration acceleration which is 1 times the previous sinusoidal excitation signal to make the shaker vibrate periodically. The sampling frequency of the system is 90Hz, and the collection frequency of the force balance sensor is 55Hz. The design vibration time of the shaking table is 90s. After the data is obtained, the data is analyzed in time and frequency domain using MATLAB software, and the calibration curve is drawn by comparing the data. Figure 5 shows the acceleration spectrum of the MEMS sensor in the y-axis direction.

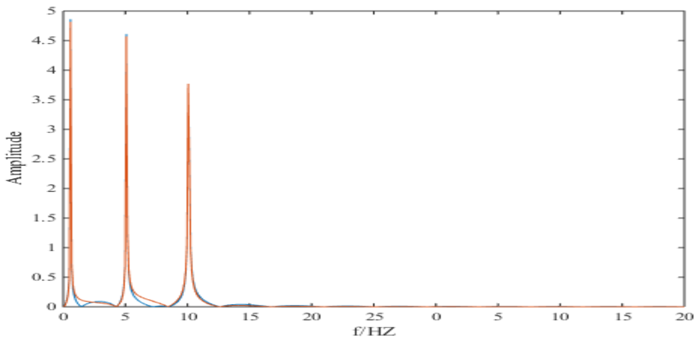

Figure 5. Y-axis frequency domain signal diagram of MEMS sensor

As shown in the figure above, the time domain diagram of the y-axis of the force balance sensor and the MEMS acceleration sensor are basically the same, but because the accuracy and anti-interference ability of the MEMS sensor is worse than the force balance sensor, it can be seen that the noise in the frequency spectrum of the signal collected by the MEMS sensor is more obvious. In order to calibrate the sensor data more accurately, a section is taken from the stable time domain signals of the two sensors for data comparison and calibration.

4.2. Analysis of Experimental Results of Each Sensor

According to the sinusoidal characteristics of the signal, in the case that point-to-point calibration cannot be performed, this paper first uses MATLAB to perform a Fourier curve fitting to obtain a fitting function and then performs amplitude calibration. The y-axis acceleration curve fitting function of the MEMS sensor is,

$$f(t)=4.082+37.77\cos(6.705*t)+278.9\sin(6.705*t) \tag{1}$$

The acceleration curve fitting function of the force balance sensor is obtained as,

$$f(t)=-1.869-135.4\cos(6.403*t)+198.1\sin(6.403*t) \tag{2}$$

Because the accuracy of the sampling frequency has a certain limit and the fitting error of MATLAB causes the frequency deviation of the above formula, the previous DC deviation is the signal measured when the initial acceleration is 0, and it can be adjusted by 0 before use. According to the two formulas, the amplitude of the x-axis acceleration of the MEMS sensor is $\sqrt{(37.77)^2+(278.9)^2}=281.446$, and the amplitude of the force-balanced acceleration sensor is $\sqrt{(-135.4)^2+(198.1)^2}=239.952$, so after calibration, the true value of the x-axis signal of the MEMS sensor is:

$$y'=\frac{239.952}{281.446}y=0.853\cdot y \tag{3}$$

Among them, y is the acceleration value measured by the MEMS acceleration sensor after initial adjustment of 0, 0.853 is the correction coefficient, and y 'is the output correction value. The resulting acceleration time-domain signal diagram is shown in Figure 6.

As can be seen from the figure, the z-axis time domain diagram of the force balance sensor and the MEMS acceleration sensor are basically the same, but because the accuracy and anti-interference ability of the MEMS sensor is worse than the force balance sensor, it can be seen that the noise in the frequency spectrum of the signal collected by the MEMS sensor is more obvious. In order to calibrate the sensor data more accurately, a section is taken from the stable time domain signals of the two sensors for data comparison and calibration. The vibration table test was used to calibrate the MEMS triaxial acceleration sensor using a force balance sensor, and the collected acceleration data was analyzed in time and frequency domain, and the data was calibrated by data fitting. A single pendulum test was designed to perform the acceleration sensor measurement. Performance tests show that the sensor system has good acquisition characteristics. An electronic temperature and humidity meter is designed to conduct data comparison tests on temperature and humidity sensors. The results show that the system temperature and humidity sensors have good performance. The slant table test is designed, and the electronic inclinometer is used to calibrate the system inclination sensor to obtain the data correction function.

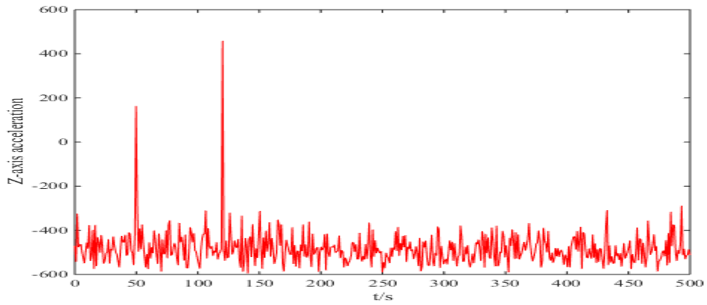

Figure 6. Time domain plot of acceleration signal

5. Conclusion

As a hotspot in the research of wireless transmission technology today, using wireless sensor networks to collect and transmit field data in industrial fields has a very broad application prospect. Aiming at the limitation of subway tunnel structure and environmental monitoring, this paper designs a tunnel structure health monitoring system based on ZigBee wireless sensor network, and verifies the design through practical applications. A good result is obtained. The comprehensive analysis of the real-time status of the tunnel data can better predict tunnel structural problems and unexpected accidents. This paper has developed an assembled wireless sensor that can monitor the interior and surface of the tunnel structure. The assembled wireless sensor consists of a traditional sensor, a signal conversion device, a signal wireless receiving and transmitting device, and an energy supply device. It overcomes the limitation that the integrated intelligent miniature sensor can only monitor the surface parameters of the tunnel structure, but not the internal parameters of the tunnel structure.

In this paper, the structure of the ZigBee protocol stack and the content and working mechanism of each layer are studied in depth. On this basis, the network topology used in this design-ZigBee tree network topology is proposed. This article aims at the processing and analysis of system data. Based on the software platform, this article designs corresponding data error correction and detection algorithms, including parity check algorithms, FLASH-based ECC data error correction and error detection algorithms, and reduce the bit error rate of data in system transmission and storage. This paper also studies the wavelet denoising algorithm, and uses the wavelet denoising algorithm based on sym8 wavelet to remove the interference and noise from the system sensor data to improve the validity of the system data. At the same time, according to the fuzzy processing method, a tunnel structure health evaluation model is established, and a tunnel structure health evaluation algorithm based on a random forest is designed to comprehensively evaluate the overall operation status of the tunnel.

The health monitoring system based on wireless sensor network in this paper is composed of wireless sensors, wireless communication terminals, intelligent mesh network protocols, data management centers, intelligent analysis systems, and visual operating platforms. Compared with traditional manual and wired monitoring methods, it has excellent capabilities such as high early warning reliability, low cost, low energy consumption, passive energy supply, and wireless intelligent networking. It is also suitable for field and sudden special monitoring and early warning tasks. It provides convenience for the health of the tunnel structure and is a new development direction for the health monitoring of the tunnel structure in the future.

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Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Conflict of Interest

The author states that this article has no conflict of interest.

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