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Original Paper

Embedded Water-lubricated Bearing Temperature Wireless Monitoring System

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Abstract

For the ship lubrication system, different water temperatures not only affect the viscosity coefficient of the water, but also cause additional thermal deformation of the rubber bearing, and in serious cases, it also affects the normal operation of the ship lubrication system. However, the water film has a closed area, various bearing structures, complex operating conditions, and limited existing monitoring methods, resulting in accurate temperature data that is not easy to obtain. In order to solve the above problems, a thin-film temperature sensor was proposed to be embedded in the water-lubricated bearing and wireless communication technology was applied, and a monitoring system was developed to achieve real-time monitoring of the bearing temperature signal. Firstly, the temperature monitoring system and bearing system are described, then the temperature sensor is calibrated, and finally the system is designed and tested through software and hardware. The results show that the method of the wireless temperature monitoring system in this paper is feasible.

Keywords

Water-lubricated bearings, Embedded, Temperature monitoring

1. Introduction

Because the ship will produce more heat under heavy load conditions, and the temperature of the water area where the ship is located will also be affected by the region and the season, for the ship lubrication system, different water temperatures not only affect the viscosity coefficient of the water, but also cause additional thermal deformation of the rubber bearing, and in serious cases, it will also affect the normal operation of the ship lubrication system. Ships working in the water often face a variety of harsh environments, such as more impurities in seawater, and sediment will enter the shaft system near the shore, which can easily affect the performance of the bearing, and if it fails, it may lead to direct failure of the bearing. Therefore, it is necessary to study the influence of thermal effects and complex working conditions on the lubrication performance of water-lubricated rubber bearings.

An embedded rolling bearing inner ring wireless testing scheme is proposed, which realizes signal transmission through wireless sensing technology and applies wireless magnetic power supply to the system, realizing real-time monitoring of inner ring temperature (Zhu Yongsheng, Zhang Pan, Yuan Qianqian, et al., 2019; Wang Fangzhe, Zhu Yongsheng, Yan Ke, et al., 2018); Temperature sensors are proposed to be embedded into the outer ring of rolling bearings to monitor the bearing temperature, and the structural design problem of embedded smart bearings is investigated based on the finite element method; By analyzing the relationship between the maximum deformation and the maximum stress of the bearing outer ring to determine the bearing outer ring groove size, to provide a basis for the selection and design of the sensor module (Chen Jinhai, Zhang Wenyuan, Luo Mengting, et al., 2021; Chen, J. H., Zhang, W. Y., & Wang, H., 2021). Fiber optic sensors are embedded in bearings to enable thermal condition monitoring in their application environments (Eugenio Brusa, Matteo Dalla Vedova, Lorenzo Giorio, & Paolo Maggiore, 2019). A structure with fiber-optic grating sensors embedded in water-lubricated bearing rubber shaft tiles was designed, and a monitoring system was developed to conduct various types of condition-monitoring tests on rubber shaft tiles using an elastomer testing machine with reference to the state of the water-lubricated shaft bearing force during actual ship operation (Yu Xiaofeng, Shuai Changgeng, Yang Xue, et al., 2022; Yu, X., Shuai, C., Yang, X., et al., 2022); An innovative design method for water-lubricated bearings in ships is proposed, and the feasibility of the design scheme is verified using a friction testing machine (Xue Enchi, Guo Zhiwei, Yuan Chengqing, et al., 2022; Xue, E., Guo, Z., Zhao, H., et al., 2022).

A revolutionary bearing condition management technology, SKF Insight, is proposed, integrating multiple sensors with wireless signal transmission, embedded networking, and self-generation (SKF partners with Siemens to improve railway reliability final, 2018). The spindle displacement measurement system Spindle Sense has been launched containing modular displacement sensors to measure radial and axial displacement and tilt of the spindle at actual load and speed in high resolution (Schaeffler. Schaeffler Spindle Sense Reduces Machine Downtimes, Increases Utilisation Of Machine Capacity, 2020). By integrating a wheel bearing containing a three-axis load sensor and a rotation sensor with an isotropic universal joint, an isotropic universal joint wheel bearing unit has been developed (Hashizume Shohei, Shibuya Yusuke, Kondo Daichi, et al., 2021). The developed axlebox bearings with sensors for railroad coaches are widely used in the field of railroad trains. The sensor bearings have various sensing functions to monitor the bearing temperature, vibration, and rotational speed (Yang Liu, 2019).

Based on the above research, this paper proposes an embedded water-lubricated bearing temperature wireless monitoring system, and designs a thin-film sensor embedded water-lubricated bearing structure, i.e., the sensor is embedded into the axial tile and combines with wireless communication technology to form a unique bearing structural unit in order to realize real-time and accurate monitoring of the bearing temperature.

2. Overall Program Design of the Monitoring System

The embedded water-lubricated bearing temperature monitoring system is shown in Figure 1, including 3 parts: sensor technology, hardware design and software design. Since the sensor is mounted inside the bearing and space is limited, its size must be small, so a thermocouple temperature sensor is selected and its calibration and mounting methods are studied. Consider signal transmission and circuit integration. It is proposed to integrate the signal acquisition, analysis and transmission circuits into a single circuit board, which is made into a ring shape to be mounted inside the end cap of the bearing housing and integrated with the bearing. Since the sensor is installed inside the axial tile, directly in contact with the bearing lubrication interface, more accurate data on internal temperature changes can be obtained; the data transmission adopts wireless communication, and the XBee3 module (Zigbee protocol) is used to build a communication test system to ensure the correct transmission of data.

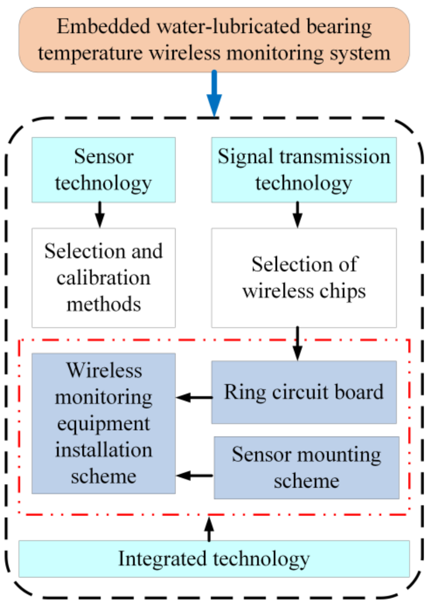


Figure 1. Technical Route

The structure of embedded water lubricated bearing is shown in Figure 2. Since the bearing is in a confined space, a thermocouple temperature sensor is selected and embedded in a slot in the axial tile; In addition, too many cable switches will lead to installation and commissioning inconvenience, the circuit design needs to meet the requirements of functional integration and miniaturization of the structure, the choice of double-layer PCB boards to reduce the problem of staggered wiring, in order to reduce the size of the circuit board, the components to choose the SMD type; The data acquisition processing and communication circuits are integrated in the same ring circuit board, which is coaxially mounted at the bearing end cap, and radial holes are set at the end cap for the antenna, and sufficient safety distance is reserved near the antenna to prevent interference; small holes are punched axially through the axial tile to wear the sensor signal line and connect it with the integrated ring circuit board. Shaft in the process of rotation will be collected by the sensor will be transmitted to the rotor system outside, by the wireless sensing equipment to receive and send to the host computer software processing and analysis, complete the real-time monitoring of temperature data.

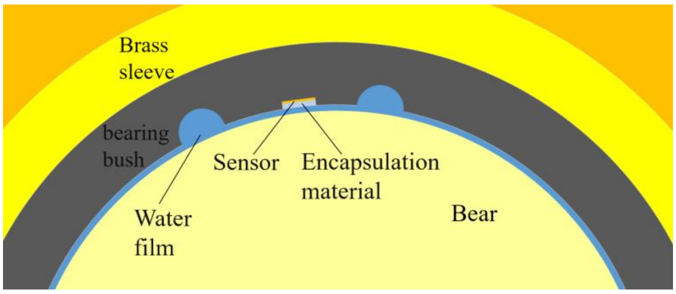


Figure 2. Embedded Water-lubricated Bearing Construction

3. Sensor Selection and Calibration

Temperature sensor types include thermocouples, thermistors (NTC/PTC), resistance temperature detectors (RTD), etc., which have their own advantages and disadvantages. For example, thermocouples have the advantages of wide temperature measurement range, fast response speed, high reliability, etc., but the accuracy is relatively low; thermistors are inexpensive and sensitive, but the linearity is poor; RTDs have high accuracy and good stability, but the cost is high. Specific parameters in Table 1, in the selection, need to weigh and choose according to the specific application requirements and the actual situation.

Taking into account further factors such as measuring range, mounting dimensions, and installation environment, thermocouple sensors are selected mainly because of their small size and suitable measuring range.

Table 1. Technical Parameters of Commonly Used Temperature Sensors

Technical Reference	Thermocouples	Platinum RTD	DS18B20
Temperature range	-270~1800℃	-250~900℃	-55~150℃
Sensitivity	above average	general	general
Temperature measurement accuracy	±0.5℃	±0.5℃	±0.5℃
Output form	voltage	resistive	digital signal

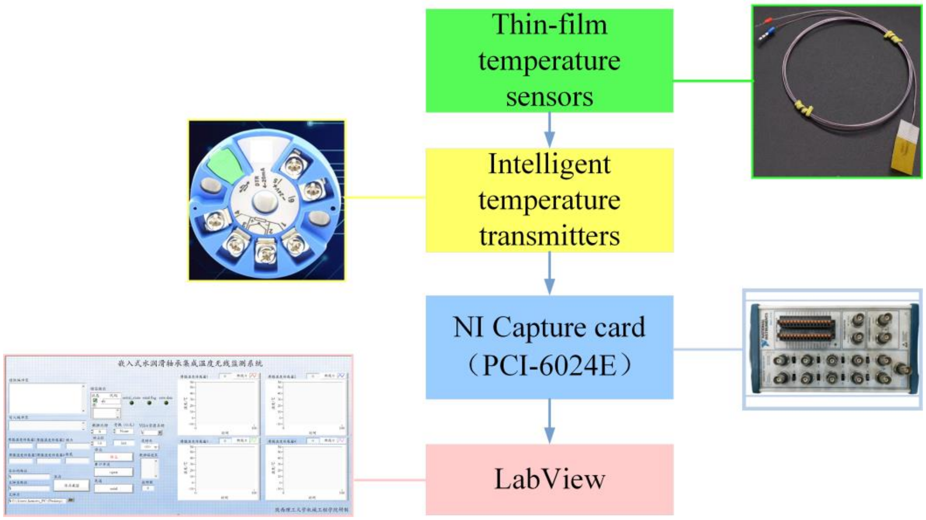


Figure 3. Temperature Sensor Calibration Process

The thin-film temperature sensor calibration process and data processing process are as follows:

(1) the first thin film temperature sensor and transmitter connected to the sensor selection using the K-type thermocouple Kaepernick surface paste temperature sensor, transmitter selection matching Kaepernick intelligent temperature transmitter, which has a built-in anti-reverse connection circuit; disconnection detection function; π-type EMI filtering circuit, which can cope with most of the industrial field interference signals; measurement signals and ranges can be debugged through a special cable from the cell phone (or) special debugging equipment to modify the corresponding parameters; the core using imported MCU 24bit ADC precision sampling, the actual measurement accuracy is better than 05%. Measuring signal and range can be modified from mobile phone (or special debugging equipment) through special debugging cable; the core adopts imported MCU, 24bitADC precision sampling, the actual measurement accuracy is better than 0.05%.

(2) Connect the transmitter output signal to the NI acquisition card (PCI-6024E type), and display and save the voltage value of the acquired temperature signal on the upper computer panel.

(3) Analyze the collected signals. Thin-film temperature sensor received temperature changes and the resulting voltage signal is a linear relationship, so the collected data were linear regression analysis, the use of least squares to fit the sensor temperature and voltage linear equation, that is, to complete the sensor calibration. Calibration results are $T = 0.87647 + 0.04296U$ (T: temperature, unit: °C; U: voltage, unit: V); As can be seen in Figure 4, the sensor linearity is good.

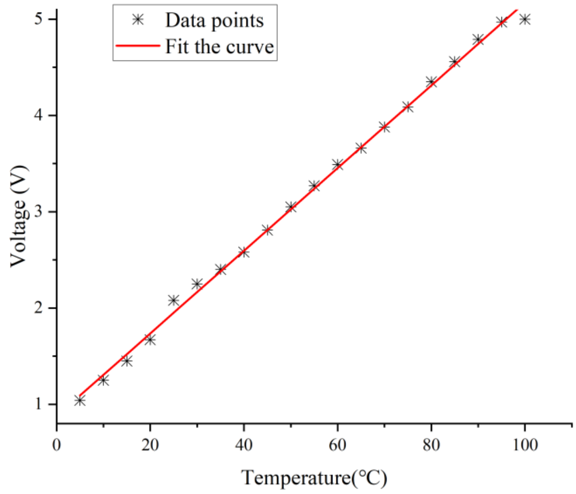


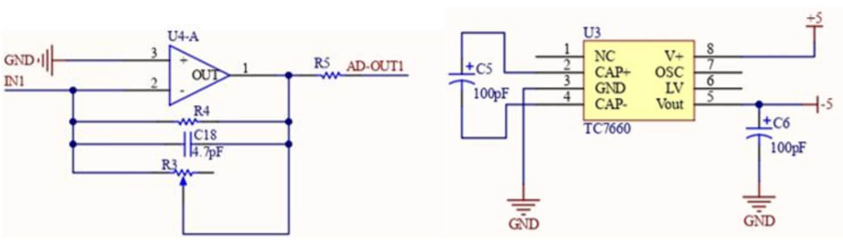
Figure 4. Calibration Results

4. Hardware Design

4.1 Signal Conditioning Circuit Module

Due to the existing water lubricated rubber bearings of large size, the use of thin-film temperature sensors only to its multi-point acquisition in order to respond to a more comprehensive bearing lubrication and temperature changes, however, thermocouples produce a potential is usually only a few millivolts to tens of millivolts, such voltage levels are not enough to be analyzed directly by the microcontroller analysis and processing, so it is also necessary to capture the circuitry to carry out accurate linear amplification.

Operational amplifier selection MCP6004, MCP6004 as a four-channel low-power operational amplifiers, DC voltage converter selection TC7660, low-cost design of the acquisition circuit module external regulated power supply for 5V power supply, support for eight-way temperature sensor work at the same time, as shown in Figure 5.



(a) Single-channel amplification circuit (b) TC7660 module

Figure 5. Schematic Diagram of the Signal Acquisition Circuit

4.2 Microcontroller Module

The microprocessor is STM32F103C8T6, based on Cortex-M3 core, and PA1, PA2, PA3, PA4 of STM32 are used as the data acquisition pins to connect with the sensor acquisition circuit, and PA9, PA10 are used as the serial data transmission pins to connect with the XBee3 terminal node. In the design of the STM32 master control hardware circuit, it mainly includes the download circuit module, power module circuit, clock circuit, reset circuit and external pin circuit, etc. The schematic diagram of the master control circuit is shown in Figure 6.

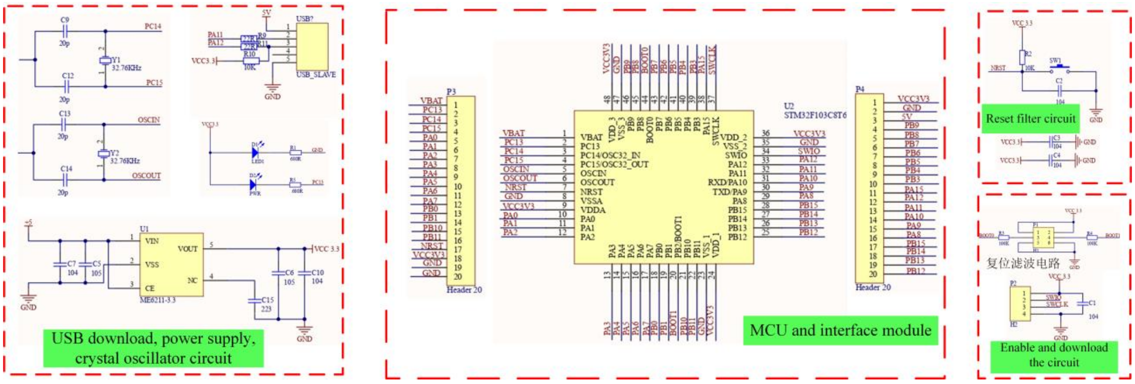


Figure 6. Schematic Diagram of the Main Control Circuit

4.3 Wireless Transmission Module

This paper adopts the XBee3-24Z8ST-J wireless data transmission module, as shown in Figure 7, the module can be divided into terminal node device and coordination device after configuration, the terminal device module through a UART serial interface and external microcontroller data interaction, the coordination device through the USB-mini interface and the host computer for data communication. XBee3 communication adopts transparent mode, i.e., data transmission in AT mode. In transparent mode, the module can be used as a serial port of the microcontroller, and the two XBee3 modules are under the same network PAN ID, and the MAC address of the terminal node (coordinator) is set as the target address of the coordinator (terminal node), and the collected data goes into the serial UART interface of the XBee3 terminal node module, and will be sent to the coordinator module with the target address specified. The collected data enter the serial UART interface of XBee3 terminal node module, and will be sent to the coordinator module specified by the target address, and output from the serial port of the coordinator module and displayed to the host computer interface.

Figure 7. XBee3-24Z8ST-J physical drawing

4.4 Integrated Design

Rotating machinery in order to prevent too many cables and signal perturbation, this paper designs a temperature monitoring ring, the ring circuit board (Figure 8) embedded in the bearing end cap, the temperature sensor cable connects the ring circuit board to transmit the signal to the XBee3 terminal node, which in turn transmits the signal to the coordinator and finally displays real-time temperature changes of the bearings on the host computer in order to achieve the real-time monitoring of the bearing temperature condition.

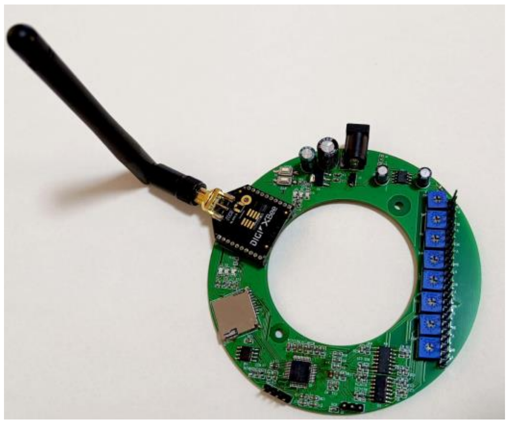


Figure 8. Ring Circuit Board

5. Software Design

5.1 Serial Port Data Communication

The software development of the lower computer uses Keil5 software as the development environment and C language as the main programming language, and the flow chart of the system software design is shown in Figure 9. The lower computer software system program needs to be written with STM32F103C8T6 as the carrier, and the modularization idea is adopted to carry out the programming, and the program mainly includes: initialization of the STM32 system, acquisition of data by multiple ADCs, serial port data parsing and data communication.

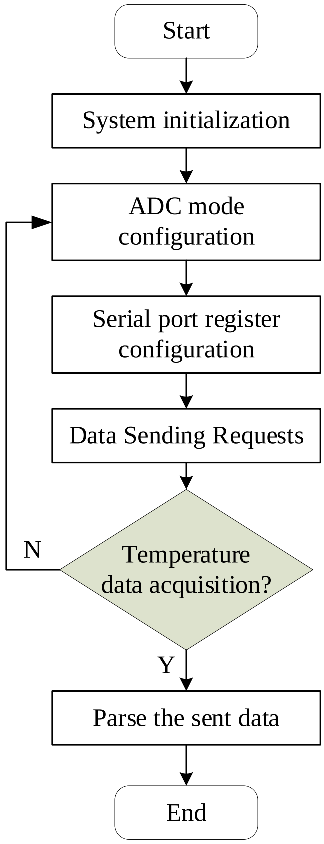


Figure 9. **Main Program Flow Char**t

5.2 Human-computer Interface Development

In order to facilitate the observation of real-time temperature data, Labview temperature wireless monitoring and analysis software has been developed, which has a friendly interface and good maneuverability. Interface as shown in Figure 10, the software back panel program while loop, event structure, can realize the multi-channel water membrane pressure wireless signal real-time reception, monitoring, storage and analysis functions. The software integrates the program of decompression and decoding of the received compressed data, and after all the background programs are packaged and processed, the software can be run on any computer.

Test site as shown in Figure 11, through the pilot test, can achieve real-time monitoring of water-lubricated bearing temperature data, and relative to other monitoring methods closer to the real value, and to achieve the purpose of real-time monitoring.

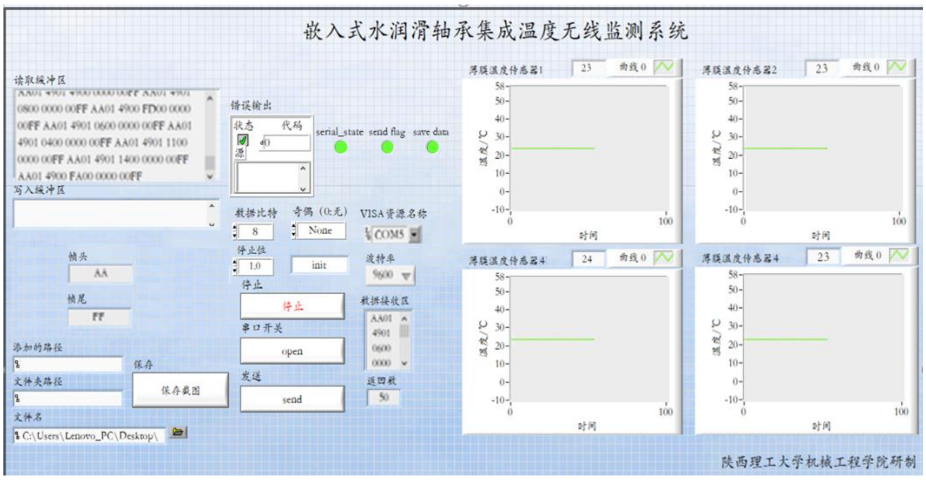


Figure 10. Front Panel of the Host Computer

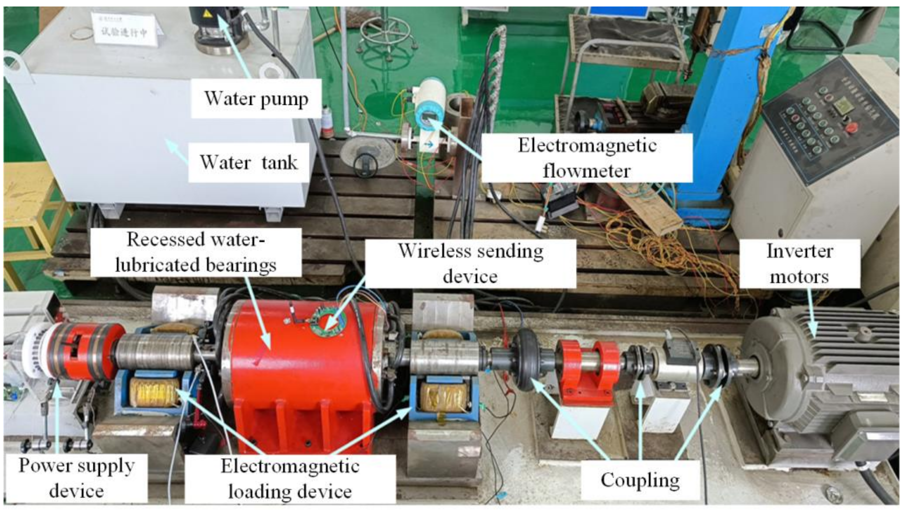


Figure 11. Test Site

6. Conclusion

(1) Due to the limited maneuverable space of water-lubricated bearings, the traditional bearing monitoring method has difficulty in approaching the measurement point, and the sensor is too large and may damage the structure of the shaft system. Therefore, the combination method of bearing and sensor is studied, and the thin-film temperature sensor is selected as embedded inside the water-lubricated rubber bearing shaft tile, and the calibration method is proposed and the calibration system is established to obtain the conversion relationship between temperature and voltage.

(2) According to the embedded water lubrication bearing temperature monitoring system hardware functional requirements, to take the “modular” design principle, sub-module signal acquisition in the integrated circuit board, the main control chip, wireless transmission and other parts of the detailed analysis, the development of an integrated ring circuit board, at the same time, with the help of the upper computer software development of human-machine interactive interface, to achieve the

parameters of the real-time monitoring.

(3) In wireless sensing technology, integration technology, designed the embedded water lubrication bearing temperature monitoring system, the wireless ring circuit board integrated installation in the bearing end cover to build the monitoring system, and test, to verify the temperature monitoring system in this paper is feasible.

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