Multi-functional Patrolling Device for Pump Stations

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Abstract. The South-to-North Water Transfer Project (SNWTP) represents a critical infrastructure initiative aimed at mitigating water shortages in northern China. Integral to this project is the efficient operation of pump stations, such as the Baoying Pump Station, where the operational demands necessitate continuous, rigorous patrols to ensure functionality and safety. The traditional patrol process, which involves multiple inspections within an 8-hour shift, is labor-intensive and time-consuming, requiring approximately 315 minutes per shift. This paper introduces a multifunctional patrolling device specifically designed to enhance the efficiency and effectiveness of these inspections. The proposed device integrates various essential functions, including power management, real-time clock, OLED display, intercom, lighting, NFC sensing, Bluetooth transmission, and the measurement of temperature, noise, and vibration. By consolidating these functionalities into a single portable device, the patrol time is significantly reduced, improving operational efficiency and reducing labor costs. The device's modular design also allows for easy maintenance and future upgrades, ensuring its long-term viability in industrial environments. SolidWorks was employed to optimize the design of the device, resulting in a final assembly that is robust, lightweight, and user-friendly. The implementation of this patrolling device in the Baoying Pump Station has demonstrated a reduction in patrol time from 315 minutes to 230 minutes per shift, representing a 27% improvement in efficiency. This paper concludes that the multifunctional patrolling device not only enhances operational efficiency in pump stations but also has the potential for broader application in various industrial settings, where similar inspection routines are required.

1. Introduction

The South-to-North Water Transfer Project (SNWTP) is one of the most ambitious and significant water diversion initiatives ever undertaken, aiming to address the severe water shortages in northern China by diverting water from the south, where it is more abundant. The project consists of three main routes: the Eastern, Central, and Western routes. The Eastern Route is the most technologically complex of the three and was the first to be constructed. It starts from the Yangtze River, specifically from the Jiangdu Pumping Station in Jiangsu Province, and travels northward to Tianjin, passing through several key provinces, including Shandong and Jiangsu. This route utilizes a series of existing canals and rivers, such as the Grand Canal, combined with newly constructed pumping stations and tunnels, to facilitate the flow of water. The Baoying pump station is the second major booster in the line, where 13.6 MW pump facilities are installed.

In accordance with the operational guidelines for pump station management [1], a continuous 24-hour duty cycle is mandated during pumping operations, with shifts structured into 8-hour intervals.

Each shift includes four designated patrols: three within the pump station, conducted at 2-hour intervals, and one comprehensive patrol spanning the entire shift duration. During the station patrols, personnel are required to be equipped with essential tools, including a flashlight, intercom, noise meter, vibration meter, and temperature gun. Each station patrol is completed within approximately 70 minutes. The comprehensive patrol, which similarly necessitates the use of these tools, requires an extended duration of approximately 105 minutes. Consequently, the cumulative time for completing all patrols within a single shift amounts to 315 minutes, which has been observed to contribute to a reduction in operational efficiency.

A comprehensive analysis of the factors limiting patrol efficiency in the project reveals several key challenges. Firstly, the variety of patrol tools, coupled with their large size and significant weight, hampers operational efficiency. Secondly, frequent tool switching during patrol inspections substantially increases time consumption. Thirdly, prolonged load-bearing during patrols leads to a decline in staff productivity. In such engineering applications, there is a substantial market demand for multifunctional integrated measuring equipment.

This paper introduces a multifunctional patrol machine designed to address the current market deficiencies of such equipment. The proposed device adheres to the principles of lightness, flexibility, robustness, and durability. It is portable, streamlines the inspection process, and reduces the operational challenges faced by patrollers. The equipment's internal modular design facilitates maintenance, functional upgrades, and adherence to industrial patrol inspection standards. The structure of this paper is as follows: Section II provides an in-depth analysis of the technical implementation scheme for the patrol machine. Section III presents the design of the basic modules, while Section IV details the design of the functional modules. Section V discusses the design and assembly process. Finally, the conclusions are presented in Section VI.

2. System Architecture

The design philosophy of the system depicted in the diagram focuses on modularity, integration, and efficiency. Each module within the system is designed to perform specific functions while working cohesively under the management of a centralized power management and system control unit. Here’s a breakdown of the key aspects of the design consideration.

Independent Functional Modules: The system is composed of multiple independent functional modules, such as intercom, LED lighting, temperature measurement, vibration measurement, and noise measurement. Each module is designed to perform its specific task independently, allowing for easy upgrades, maintenance, and potential future enhancements.

Flexible System Configuration: The modular design allows for the flexible configuration of the system based on specific operational needs. Modules can be added, removed, or replaced without disrupting the overall functionality, providing scalability and adaptability.

Centralized Management: All modules are integrated and managed by a centralized power management and system management unit. This unit ensures that all components operate in harmony, optimizing power distribution, data processing, and overall system efficiency.

Seamless Communication: The integration of NFC sensing and Bluetooth transmission modules [2, 3] enables seamless communication and data exchange within the system. This ensures real-time data processing and transmission, which is critical for timely decision-making and efficient operation.

Optimized Power Usage: The system employs a pouch Li-ion battery for its power supply, which is managed centrally to optimize energy usage across all modules [4]. This design choice is crucial for ensuring long operational times and reducing the need for frequent battery replacements or recharges.

Data Management and Control: The inclusion of data storage and transmission modules, along with a user joystick control, enhances the system's efficiency in managing and processing data. The OLED display provides real-time feedback to the user [5], facilitating informed decisions and effective system control.

User-Friendly Interface: The inclusion of a user joystick control and an OLED display suggests a focus on creating an intuitive and user-friendly interface. This design choice enhances the usability of the system, making it accessible to operators with varying levels of technical expertise.

The system architecture is proposed as in Fig. 1.

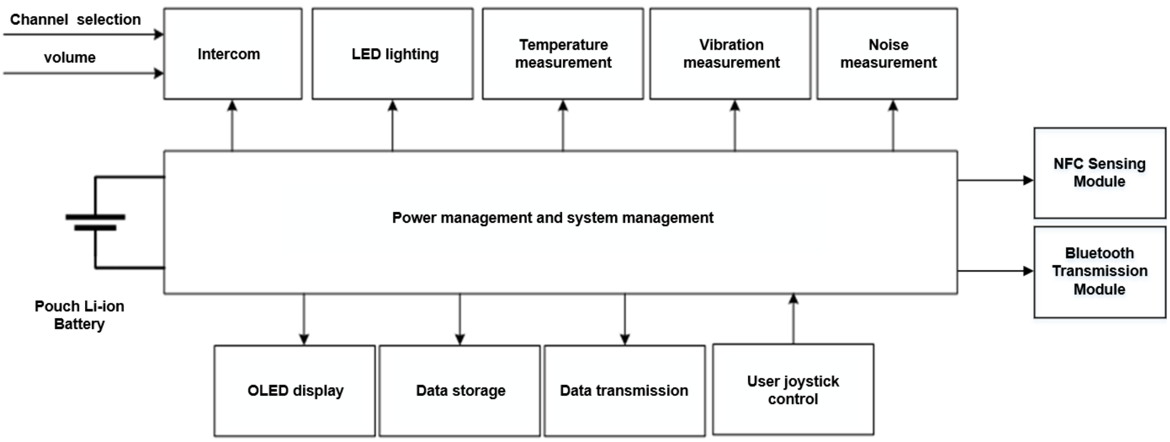


Fig. 1. System diagram.

The detailed design of power supply, modules and data flow are shown in

Fig. 2. Basic modules design includes power supply, real-time clock, OLED display, intercom and lighting. The intercom function shall meet the normal communication between the 7th floor of the pump station, have noise reduction function, amplify and receive weak wireless signals to meet clear intercom, and have certain penetration to walls and other objects. The lighting function shall meet the minimum illumination distance of 50 m, the minimum brightness of 200 lumens and the minimum continuous lighting time of 1h.

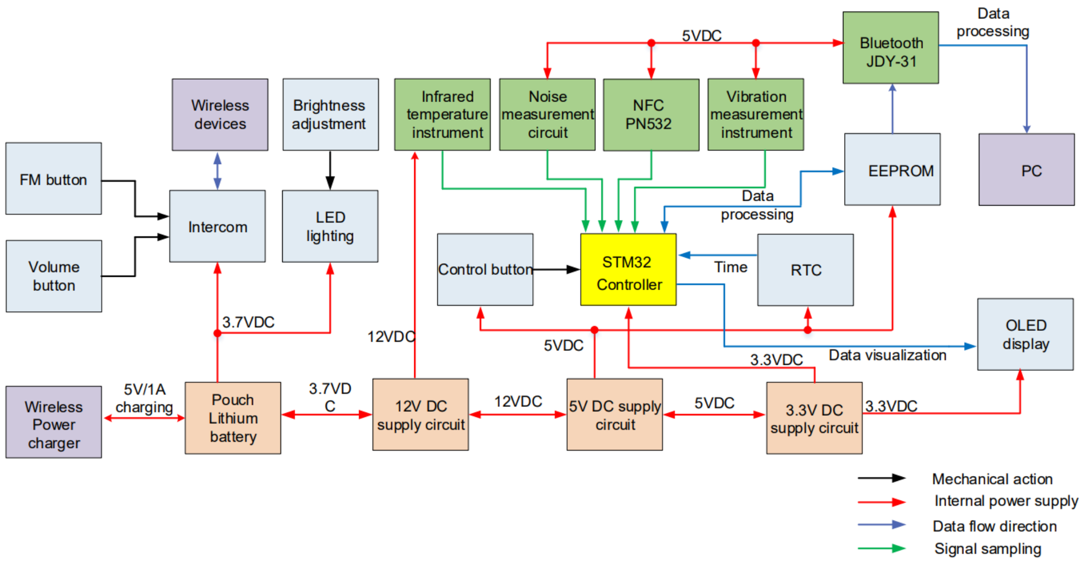


Fig. 2. Function blocks with power and signal flow.

The functional module design of the all-in-one patrol machine for pump stations includes an NFC sensing module, a Bluetooth wireless transmission module, and modules for measuring temperature, noise, and vibration. The NFC sensing module is responsible for identifying station IDs. The temperature measurement function covers the entire temperature range of the measured object, with a maximum error of ±2 °C across the full range. For local temperature measurements, the accuracy is improved to ±1 °C. The noise measurement range spans from 35 to 130 dB, with a maximum linear error of 1% of the measured value. This module is equipped with full-range temperature compensation [6-8], data correction features, strong anti-interference performance, and a noise detection data query function. Vibration measurements are conducted via contact measurement, with a displacement range of 0.01 to 1.5 mm, and include a vibration detection data query function.

Upon completion of each patrol, the Bluetooth wireless transmission module is crucial for uploading data to a PC. The patrol machine is capable of storing measured data, facilitating efficient data management, intelligent report processing, and trend chart generation. The data report format is standardized as “time + location + function + measured data.” The data visualization function enables the display of historical measurement data, ensuring it meets the requirements of continuous patrol inspection, and assists inspectors in the accurate and effective measurement of the object. Lastly, SolidWorks was employed to design the assembly of the all-in-one patrol machine.

3. Basic Modules Design

3.1 Power supply module

The use of pouch lithium-ion batteries is favored due to their assembly-friendly form factor. The specific battery under consideration operates at 3.7 V with a capacity of 5000 mAh and a charging cut-off voltage of 4.2 V. Given the system's reliance on three voltage levels — 5 V, 12 V, and 3.3 V — it is imperative to design a multi-stage auxiliary power supply circuit to ensure stable and reliable circuit operation. Due to the variability in the first-stage input voltage, the MIC2288YD5-TR DC-DC switching power supply chip, which supports a wide input voltage range of 2.5 V to 10 V, has been selected, as illustrated in Fig. 3. Appropriate feedback sampling resistors, R25 and R26, are chosen to configure the output voltage to 12 V.

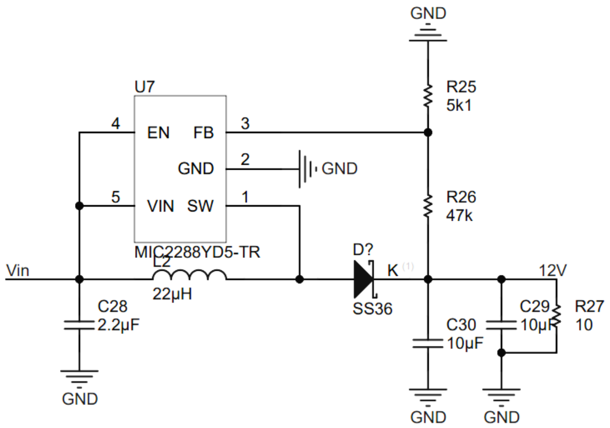


Fig. 3. Schematic diagram of MIC2288.

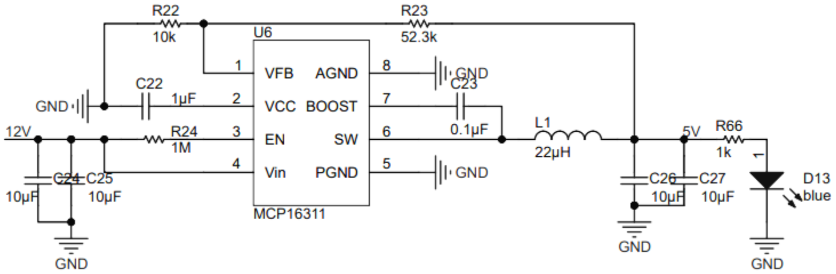


Fig. 4. Schematic diagram of MCP16311.

The second-level power conversion chip must satisfy the requirements of an input voltage of 15 V and a constant output voltage of 5 V. It should also possess robust dynamic adjustment capabilities to prevent system malfunctions due to unstable power supply. For this purpose, the MCP16311 synchronous step-down switching DC power chip, manufactured by Microchip, has been selected, as depicted in Fig. 4. This chip offers a power conversion efficiency of up to 95%, supports an input voltage range of 4.4 V to 30 V, and provides an adjustable output voltage range from 2.0 V to 24 V within a closed-loop configuration. The PWM frequency can reach up to 500 kHz, ensuring low ripple in the output voltage and thereby maintaining high output voltage quality. By selecting appropriate feedback sampling resistors, R22 and R23, the output voltage is maintained at a stable 5 V.

For the third-stage output, the AMS1117 series linear regulator, illustrated in Figure 5, has been employed. This series offers six output voltage levels: 1.5 V, 1.8 V, 2.5 V, 2.85 V, 3.3 V, and 5 V, with a maximum output current of 1 A. The display module is powered by the AMS1117CS-3.3 regulator, providing a stable 3.3 V power supply level.

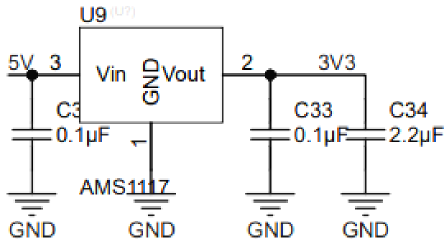


Fig. 5. Schematic diagram of AMS1117.

3.2 Real-time clock module and memory module

As illustrated in Fig. 6, the real-time clock (RTC) module [8, 9] is implemented using the DS1307 RTC chip, which operates at a voltage of 5 V. The DS1307 is a low-power clock chip featuring 56 bytes of non-volatile SRAM and fully binary-coded decimal counting. It communicates address and data information serially via a bidirectional I2C bus. By selecting an appropriate crystal oscillator, the chip accurately provides timekeeping information, including seconds, minutes, hours, day of the week, date, month, and year. The chip automatically adjusts for months with fewer than 31 days and accounts for leap years. The clock can operate in either a 24-hour format or a 12-hour format with an AM/PM indicator. The DS1307 includes a built-in power detection circuit that monitors power failure and automatically switches to a standby power supply, ensuring uninterrupted timekeeping. The standby power is provided by an LIR2032 button cell battery.

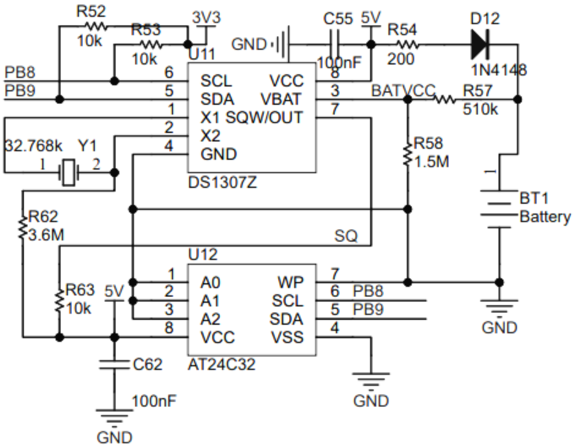


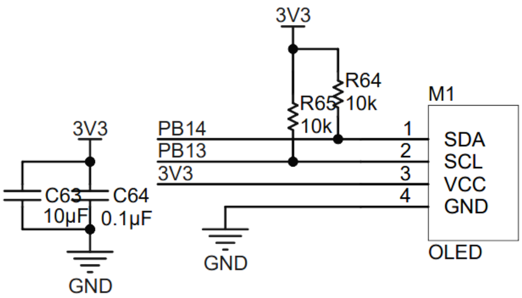
Fig. 6. Schematic diagram of real-time clock module and memory module.

The memory module uses the AT24C32 chip from Atmel, which offers 32 kbits of storage across 8 pages, with each page capable of storing 4086 bits of data. Similar to the RTC chip, the memory chip utilizes the I2C communication protocol, allowing it to be cascaded with the controller [10]. The memory operates within a voltage range of 2.7 V to 5.5 V, with a 5 V power supply chosen for this application.

3.3 OLED display module

The display module adopts SSD1309 with a display area of 55.01×27.49 mm. Compared with the ordinary LCD display, the OLED display does not need excellent characteristics such as backlight, high contrast, thin thickness, wide viewing angle, fast reaction speed, wide temperature range, simple structure and process. Due to the absence of backlight, the power consumption is also lower than that of LCD. The pixel size of this OLED display screen is 0.4 mm and the pixel spacing is 0.43 mm, which has good display effect. I2C communication interface is adopted, the working voltage is 3.3 V, and AMS1117 is used for power supply. The display module and its interface are shown in **Error! Reference source not found.**

(a) Display module



(b) Interface diagram

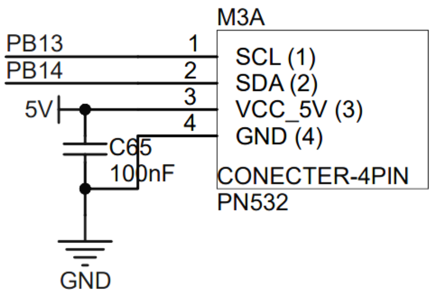
Fig. 7. Schematic diagram of display module and its interface

4. Functional Modules Design

4.1 NFC sensing module

As illustrated in Fig. 8, the PN532 RFID module has been selected as the primary component for NFC sensing. This highly integrated transmission module operates at 13.56 MHz and is capable of detecting NFC signals within a range of 5-7 cm. The PN532 supports three communication protocols: UART, SPI, and I2C. In this patrol machine application, the I2C communication interface is employed to interface with the STM32 microcontroller via the PB13 and PB14 pins. When the patrol machine is brought into proximity with a MiFare tag, the STM32, in conjunction with the PN532, is able to read the data stored on the tag.

(a) NFC sensing module



(b) Interface diagram

Fig. 8. NFC sensing module and its interface.

4.2 Temperature measurement module

The infrared temperature sensor is selected as the key component for the patrolling device in the pump station. Infrared temperature measurement technology, a non-contact method, is favored for its high accuracy and broad measurement range. However, certain external factors can influence the accuracy of temperature measurements, including the distance between the sensor and the target object, the emissivity of the target, and the surrounding environmental conditions. In the context of this application, the emissivity and environmental conditions are relatively stable, with the primary variable being the distance between the sensor and the target, which significantly impacts measurement accuracy. To address this, a distance compensation system has been designed to enhance the accuracy of the infrared temperature sensor.

An ultrasonic distance sensor is employed to measure the distance between the target object and the infrared thermometer. Temperature measurements are recorded at various distances—specifically at 40 cm, 60 cm, 80 cm, 100 cm, 120 cm, and 150 cm—to correlate the sensor readings with the actual temperature of the object, thereby improving the overall precision of the system. After thousands of tests, sufficient sample data are obtained, and the MATLAB software fitting toolbox [11] is used to measure the temperature y and the standard temperature $T(x, y)$ The data relationship is analyzed and deduced, and the following data model is obtained in combination with the test distance x:

$$T(x,y) = Ax + By^2 + Cx/y + Dxe^y + E \tag{1}$$

4.3 Noise measurement module

In this module, the noise decibel is segmented and collected [12-14]. MCP6022 is used to achieve 5.1 times, 51 times and 510 times magnification. These three amplified signals enter the DSPIC33FJ64GS101 at the same time. It selects the unsaturated signal by distinguishing the upper and lower limits of the noise signal, and continues to collect 50 sets of data to calculate the average value. Finally, the average value is DA converted to transmit the analog quantity to STM32. The specific program flowchart of noise measurement module is shown in

Fig. 9. Program flowchart of noise measurement module

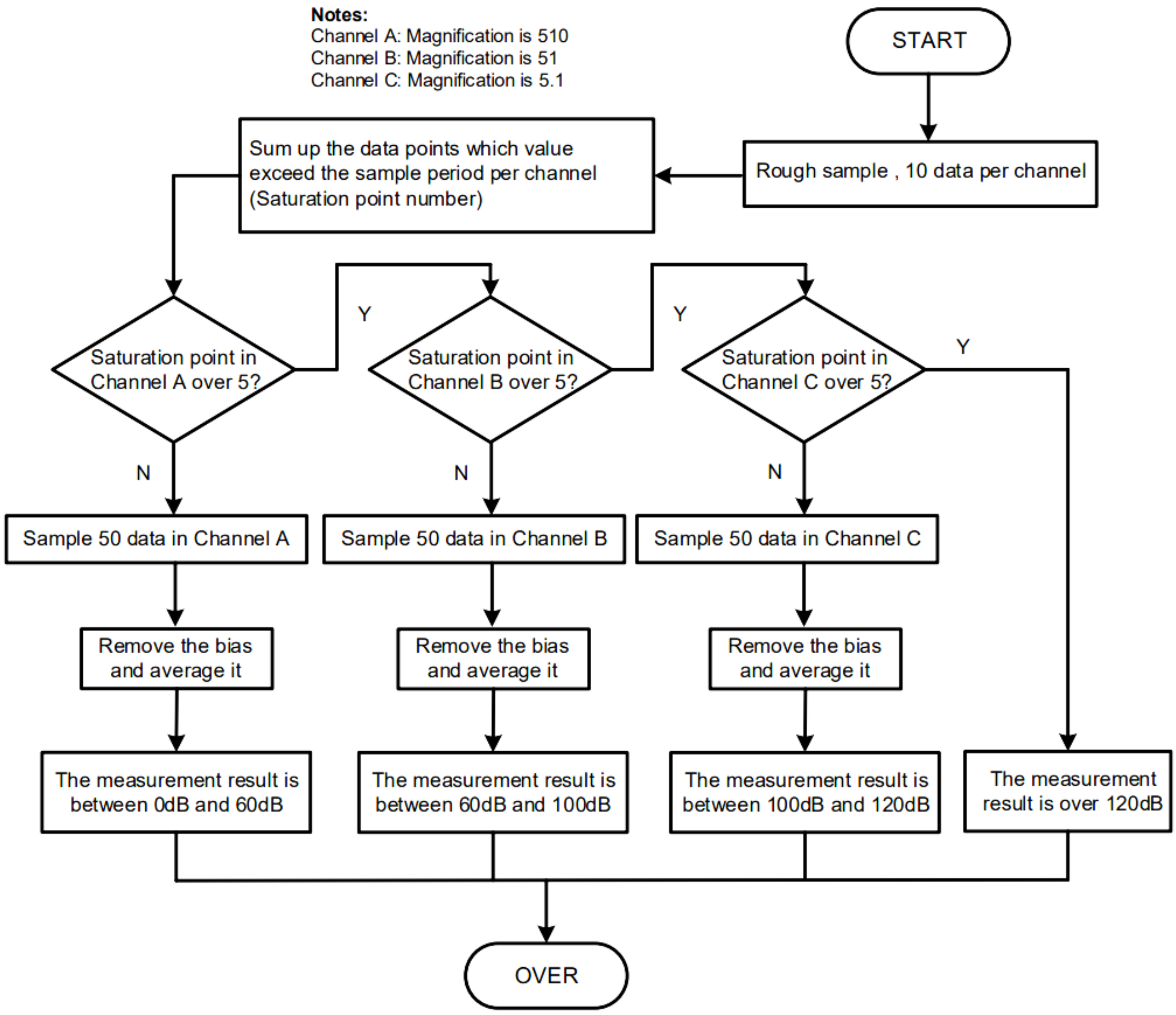


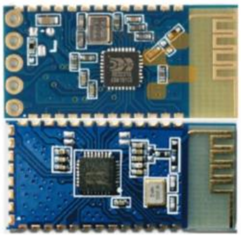
Fig. 9. Program flowchart of noise measurement module.

4.4 Vibration measurement module

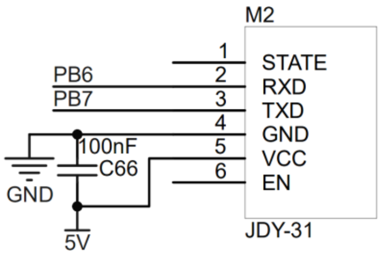
There are many types of vibration sensors. At present, the most used is the vibration sensor based on the principle of piezoelectric effect [15]. When an external force is applied to some materials (such as quartz crystal) along a certain direction to deform them, a charge will be generated on a certain surface. When the external force disappears, the charge will disappear. This phenomenon is called piezoelectric effect. In the piezoelectric vibration sensor, the sensor converts the vibration signal into charge signal through piezoelectric material and transmits it. The primary function of the conditioning circuit is to restore the charge signal to a voltage (or current) signal that is easy to detect.

4.5 Bluetooth transmission module

The patrol machine utilizes the JDY-31 module as the Bluetooth wireless transmission interface between the STM32 microcontroller and a PC, as illustrated in Figure 10. The JDY-31 module is based on Bluetooth 3.0 SPP (Serial Port Profile) design, supporting data transmission with Windows and Android operating systems [16]. It operates within the 2.4 GHz frequency band and employs Gaussian Frequency-Shift Keying (GFSK) modulation. The module features a maximum transmission power of 8 dBm and supports a transmission range of up to 30 meters.



(a) Bluetooth transmission module

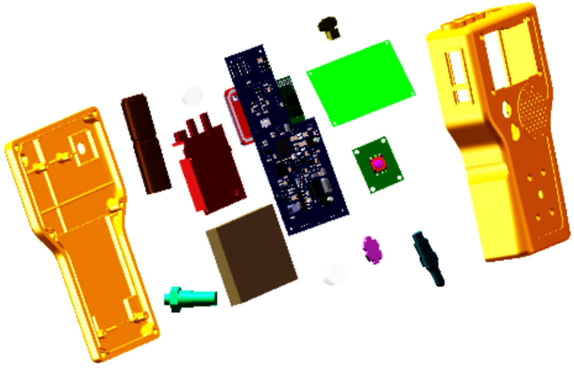


(b) Interface diagram

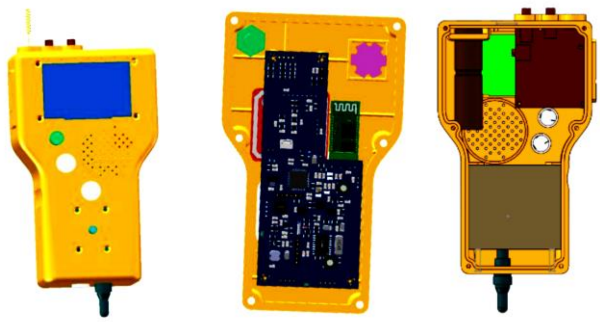
Fig. 10. Bluetooth transmission module and its interface.

5. Experiment and Results

SolidWorks is used to model and design the main control PCB[17], hardware and other modules in the system. After three versions of optimization iteration, the final assembly diagram of the patrol machine is formed as shown in the Fig. 11. Assembly diagram of all-in-one patrolling device



(a) Exploded diagram



(b) Front and rear view

Fig. 11. Assembly diagram of all-in-one patrolling device

The developed multifunctional inspection machine has been trial in the field at Baoying Station.

The main measures to reduce the time are reflected in the following:

(1) Reduce the load of equipment carried by patrol personnel and shorten the walking time of patrol personnel;

(2) Shorten the use and conversion time of various tools during patrol inspection;

(3) The patrol all-in-one machine automatically records, collects and processes patrol data, saving manual recording, entry and processing time.

A comparison of patrol times is presented in Table 1. As can be seen from the table, the inspection machine reduces the inspection time and improves the work efficiency.

Table 1. Comparison to the patrol time.

Time	Patrol pattern	Original time [min]	Current time [min]	Reduced time [min]
0:00～2:00	Per 8 hours	105	80	25
2:00～4:00	Per 2 hours	70	50	20
4:00～6:00	Per 2 hours	70	50	20
6:00～8:00	Per 2 hours	70	50	20
Data processing	4 times per shift	40	0	40
Total	8 hours per shift	355	230	125

6. Conclusions

In this paper, we proposed a multi-functional patrolling device specifically designed for pump stations, and the Baoying pump station was selected as the pilot site. This device integrates key components such as the real-time clock, OLED display, intercom, and lighting system, alongside functional modules for NFC sensing, a Bluetooth wireless module, temperature measurement, noise monitoring, and vibration detection. These features collectively reduce the inspection time for workers at pump stations from 315 minutes to 230 minutes, thereby improving operational efficiency and lowering labor costs.

The patrolling device will be further tested at Jinhu Station, with the intention of promoting its use in the operation and maintenance of large pumping stations throughout Jiangsu Province and potentially across the entire South-to-North Water Diversion Eastern Route. However, the device has yet to be tested in extreme conditions, such as high humidity or extreme temperatures, and future iterations will address these challenges. The design is also well-suited for large-scale production, enhancing its practicality for widespread use. Furthermore, the multifunctional inspection machine is adaptable to various industrial environments involving large-scale equipment, offering substantial potential for broader applications.

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