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Design and Implementation of an Intelligent Laboratory Monitoring System Based on Single-Chip Microcomputer

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Abstract: Traditional university laboratory safety management relies on manual inspection, leading to slow response, inadequate supervision and incomplete data, which brings hidden dangers to labs with precision instruments and hazardous chemicals. To solve these problems, this paper designs an intelligent laboratory monitoring system based on STM32F103C8T6 single-chip microcomputer with a modular structure. The system integrates multi-type sensors for real-time collection of temperature, humidity, illumination, smoke concentration and intrusion signals, and is equipped with OLED display, sound-light alarm and ESP8266 Wi-Fi modules. It realizes local data processing and real-time early warning, and uploads monitoring data to the cloud platform for remote visualization management. Physical tests show that the system runs stably with sensitive response, triggering alarm and uploading abnormal data within 1 second, and realizing accurate synchronization of local and cloud data. This system effectively improves the safety protection and intelligent management level of laboratories, and provides a practical solution for the intelligent transformation of laboratory safety management.

1. Introduction

1.1. Research Background and Significance

University laboratories house a large number of precision experimental instruments and hazardous chemical reagents, with complex internal environmental conditions and high safety management requirements. As an important place for scientific research and teaching, the safety and stability of laboratory operation are the basic guarantee for the smooth development of university academic work. Traditional laboratory safety management mainly relies on manual regular inspection and manual recording of environmental parameters, which has inherent defects such as slow emergency response, discontinuous data collection, and easy human supervision omissions. Once environmental anomalies such as excessive smoke concentration or abnormal temperature and humidity occur, or illegal intrusion and other security incidents happen, manual inspection is difficult to detect and alert in real time, which may lead to the expansion of potential safety hazards and even cause safety accidents such as fires and property losses[6].

In the context of the digital and intelligent transformation of higher education, the construction of an intelligent laboratory monitoring system based on Internet of Things and embedded technology has become an inevitable trend of laboratory safety management upgrading. The intelligent monitoring system can realize real-time, automatic and continuous collection of laboratory environmental and security parameters, and realize local immediate early warning and remote visual supervision. This transformation changes the laboratory safety management mode from passive post-processing to active pre-warning, effectively makes up for the blind spots of manual supervision, improves the efficiency of safety management and the speed of emergency response, and is of great practical significance for safeguarding the personal and property safety of the laboratory, standardizing the laboratory management process and promoting the intelligent construction of university laboratories.

1.2. Research Status at Home and Abroad

Foreign research on laboratory intelligent monitoring started early, and many developed countries have realized the intelligent and integrated management of laboratory environment and safety by combining embedded systems, wireless communication and cloud computing technology[6]. Foreign monitoring systems focus on the integration of multi-sensor data and the compatibility of cloud platform systems, and have achieved good application effects in the real-time monitoring of toxic and harmful gases and fire early warning in chemical and biological laboratories[1]. However, most of these systems are customized for specific laboratory scenarios, with high equipment costs and poor scalability, which are difficult to be popularized and applied in ordinary university laboratories on a large scale.

Domestic research on laboratory intelligent monitoring is developing rapidly, and many scholars have designed a variety of monitoring systems based on different single-chip microcomputers and sensor combinations. Some systems realize the basic collection and display of environmental parameters such as temperature and humidity and smoke, but lack the design of remote data transmission and cloud platform supervision, and cannot realize the remote real-time grasp of laboratory status. Some systems integrate remote communication functions, but there are problems such as single monitoring index, poor system stability and slow alarm response speed. In addition, most of the existing domestic systems focus on the functional realization of a single module, and the integration of local early warning, on-site display and remote cloud management is not high, which is difficult to meet the multi-dimensional safety management needs of modern university laboratories for environmental monitoring and security prevention.

1.3. Main Research Content and Structure

Aiming at the problems of the traditional laboratory management mode and the shortcomings of the existing intelligent monitoring system, this paper takes the STM32F103C8T6 single-chip microcomputer as the core, and carries out the research and design of the intelligent laboratory monitoring system with the core idea of modular design, multi-sensor fusion, local and remote collaborative monitoring[4]. The main research contents are as follows:

(1) Overall scheme design: Determine the modular architecture of the system, and plan the functional division and data transmission logic of each core module such as sensing detection, data processing, on-site display, alarm early warning and cloud communication.

(2) Hardware circuit design and implementation: Complete the selection, circuit design and welding debugging of each functional module including temperature and humidity, illumination, smoke, infrared intrusion sensors, OLED display, sound and light alarm and ESP8266 Wi-Fi

communication module.

(3) Software program development: Build the layered software architecture of the system, write the driver program of each sensor, the logic processing program of data collection and alarm judgment, the display program of on-site data and the communication program of data upload to cloud platform.

(4) System testing and verification: Build a physical test platform, carry out functional tests on each module of the system and the overall operation performance test, verify the stability, response speed and data accuracy of the system in actual application.

2. Related Technical Foundations

2.1. Embedded Microcontroller Control Technology

Embedded microcontroller serves as the core computing and control unit of the intelligent laboratory monitoring system, undertaking the tasks of multi-sensor data acquisition, real-time logical operation, and peripheral actuator drive[2]. The technology is characterized by high integration, low power consumption and strong real-time performance, and its core architecture adopts the Harvard structure with separated program and data storage, which realizes parallel access of instructions and data and effectively improves the processing efficiency of real-time monitoring data. The embedded control system supports modular programming and interrupt-driven response mechanisms, which can realize the priority scheduling of sensor data collection and abnormal signal alarm tasks, and ensure the timeliness of the system's response to laboratory safety risks. At the same time, the rich on-chip peripheral interfaces (GPIO, ADC, I2C, UART, etc.) of the microcontroller realize the seamless connection with various detection sensors, communication modules and display devices, laying a hardware foundation for the integration and miniaturization of the monitoring system.

2.2. Multi-Sensor Sensing and Signal Conversion Technology

Multi-sensor fusion sensing technology is the technical basis for the system to realize comprehensive detection of laboratory environmental and security parameters, and it integrates environmental perception sensors of different principles and signal types to form a multi-dimensional detection network[3]. The core of the technology lies in the accurate conversion of physical quantities (temperature, humidity, light intensity, gas concentration, infrared radiation, etc.) into electrical signals that can be processed by the microcontroller, including direct digital signal output and analog-to-digital signal conversion two forms. For digital sensors, the internal integrated signal conditioning and AD conversion circuit can output calibrated digital signals through standard communication interfaces, which avoids the interference of external signal processing and improves the accuracy of data collection; for analog output sensors, the high-precision on-chip ADC module of the microcontroller is used to complete the quantization of analog electrical signals, and through digital filtering and error correction algorithms, the noise interference in the signal acquisition process is eliminated, and the stability and reliability of the sensing data are guaranteed.

2.3. IoT Wireless Data Transmission Technology

IoT wireless data transmission technology realizes the data interaction between the local monitoring terminal of the laboratory and the remote cloud platform, and builds a bridge for the remote visual management of the laboratory[5]. The technology is based on the lightweight wireless communication protocol and the embedded network protocol stack, and selects the Wi-Fi communication module with high transmission efficiency and strong compatibility as the core communication unit, which supports the seamless access to the local area network and the Internet. The key of the technology is the packaging and transmission of monitoring data: the collected multi-dimensional data is encoded and packaged into a lightweight data format with good cross-platform compatibility, which reduces the data transmission volume and network bandwidth occupation under the premise of ensuring the integrity of information. At the same time, the wireless communication module has the characteristics of automatic reconnection and fault tolerance, which can realize the stable and continuous transmission of data in complex laboratory network environments, and support the two-way data interaction between the cloud platform and the local terminal, laying a technical foundation for the remote control and parameter configuration of the monitoring system.

2.4. Intelligent Early Warning and Local Feedback Technology

Intelligent early warning and local feedback technology is the core functional module to realize the active safety protection of the laboratory, and it integrates real-time data analysis, threshold judgment and multi-form alarm feedback. The technical core is the design of the intelligent early warning logic algorithm: the system pre-sets the safety threshold of various environmental and security parameters based on the laboratory safety management specifications, and conducts real-time comparison and analysis between the collected real-time data and the threshold value through the microcontroller. When the parameters exceed the threshold or abnormal signals are detected, the system triggers the local multi-form feedback mechanism immediately, including acousto-optic alarm prompt and visual information display. The acousto-optic alarm module adopts the electronic switch drive technology to realize the synchronous response of sound and light signals, with fast response speed and strong warning effect; the visual display module uses the low-power high-resolution display screen to realize the real-time refresh of monitoring data and the highlighted display of abnormal alarm information, which realizes the human-computer interaction of the monitoring system and the intuitive feedback of the laboratory safety status.

3. Overall System Design

3.1. Design Principles

The intelligent laboratory monitoring system is designed with the actual safety management needs of university laboratories as the core, adhering to the four principles of modular design, real-time and accuracy, local and remote collaboration, and low cost with high compatibility. Modular design ensures independent debugging and later expansion of each functional module; the real-time and accuracy principle is guaranteed by selecting high-sensitivity sensors and optimizing data acquisition processes to realize rapid response to abnormal signals; local and remote collaboration enables the local terminal to run independently and the cloud platform to realize remote supervision, avoiding monitoring failure due to network problems; low cost and high compatibility are achieved by using mature low-cost components and standard communication protocols, making the system suitable for large-scale promotion in ordinary universities and compatible with intelligent campus management systems.

3.2. Overall System Architecture

The system takes STM32F103C8T6 single-chip microcomputer as the core controller and builds a three-layer modular architecture of perception layer, control layer and application layer. The perception layer is composed of DHT11 temperature and humidity sensor, GY-30 illumination sensor, MQ-2 smoke sensor and HC-SR501 infrared intrusion sensor, which converts laboratory environmental physical quantities and security state signals into electrical signals recognizable by the microcontroller and completes primary signal conditioning. The control layer is the core of the system, including the main controller, OLED display, acousto-optic alarm and ESP8266 Wi-Fi module, undertaking the tasks of sensing data processing, threshold judgment, on-site data display, local early warning triggering and data packaging upload. The application layer is based on the cloud platform, including cloud server, data storage and visual interface, realizing remote real-time display of monitoring data, historical data storage and abnormal early warning information push, forming a closed loop of laboratory safety monitoring from data collection to remote management.

3.3. Core Functional Modules

The system is divided into six core functional modules with clear functional boundaries, which realize data interaction and collaborative operation through the main controller's internal bus and standard interfaces. The multi-parameter sensing and collection module integrates various sensors to complete real-time collection of laboratory temperature, humidity, illumination, smoke concentration and intrusion signals, and converts physical signals into processable electrical signals. The data processing and logic judgment module takes the main controller as the core, processes the original sensing data through filtering and error correction, and judges whether the parameters exceed the preset safety threshold to output corresponding control signals. The on-site display module is based on OLED screen, realizing real-time refresh display of environmental parameters and system working state, and highlighting abnormal alarm information. The acousto-optic alarm module is composed of buzzer, LED and drive circuit, triggering synchronous sound and light alarm when abnormal signals are detected. The wireless communication and cloud upload module takes ESP8266 as the core, packaging monitoring data into JSON format and uploading it to the cloud platform through Wi-Fi, and supporting remote parameter adjustment. The system power supply module adopts dual power supply design with protection circuits, providing stable voltage for each module and ensuring continuous operation of the system in case of sudden power failure.

3.4. Data Transmission Logic

The system's data transmission takes STM32 main controller as the core processing and forwarding center, following the logic of one-way main transmission plus two-way auxiliary interaction to ensure efficient and stable data transmission. The perception layer transmits digital signals directly to the main controller through GPIO/I2C interface and analog signals are converted by the main controller's on-chip ADC, realizing one-way real-time transmission of original sensing data. The main controller processes the data and unidirectionally sends valid data to the on-site display module for display, and sends control signals to the acousto-optic alarm module to trigger early warning when an abnormality is detected. Meanwhile, the main controller packages the processed data into JSON format and unidirectionally transmits it to the ESP8266 module through UART serial port for cloud upload, keeping the upload frequency consistent with the collection frequency to realize local and cloud data synchronization. On this basis, the cloud platform supports managers to issue remote control commands such as adjusting collection frequency and modifying safety thresholds, which are transmitted to the main controller through the Wi-Fi module to realize two-way auxiliary interaction of the system, meeting the needs of remote flexible management on the premise of ensuring real-time monitoring.

4. Hardware Design of the System

4.1. Overall Hardware Framework

The hardware design of the intelligent laboratory monitoring system adopts a modular integrated structure with STM32F103C8T6 as the core control chip, and the whole hardware circuit is composed of sensor detection module, human-computer interaction and alarm module, wireless communication module and power supply module. All functional modules are connected with the main controller through standard interfaces such as GPIO, I2C, UART and ADC, realizing independent circuit layout of each module and efficient transmission of data and control signals. The design follows the principles of miniaturization, low power consumption and easy wiring, with reasonable circuit layout to reduce inter-module signal interference, and industrial-grade components are selected to ensure the stability of the hardware system during long-term laboratory operation, while the simple circuit structure also lowers the difficulty of subsequent welding, debugging and maintenance.

4.2. Core Controller Module

The system selects STM32F103C8T6 as the core controller, a 32-bit microcontroller based on the ARM Cortex-M3 core, which has the advantages of fast operation speed, rich on-chip peripherals, low power consumption and high cost performance, fully meeting the system's requirements for multi-sensor data acquisition, real-time logic judgment and multi-peripheral drive. The chip is equipped with 64KB flash memory and 20KB SRAM for stable storage of system programs and collected real-time data, and is equipped with multiple GPIO ports, 3 12-bit high-precision ADCs, 2 I2C interfaces and 3 UART serial ports, enabling seamless connection with various sensors, display modules and communication modules without additional expansion chips. In the circuit design, the minimum system circuit of the controller is built including power supply, reset and crystal oscillator circuits, the crystal oscillator frequency is set to 8MHz to ensure the chip's operation speed, and the reset circuit combines manual and power-on reset to improve the controller's anti-interference ability and ensure stable system startup and operation.

4.3. Sensor Detection Modules

The sensor detection module is the system's data acquisition terminal, integrating temperature and humidity, illumination, smoke and infrared intrusion detection sub-modules, all selecting cost-effective and mature reliable sensors to achieve comprehensive detection of laboratory environmental and security parameters, with the key parameters of these core detection sensors summarized in Table 1. DHT11 is adopted for temperature and humidity detection, outputting calibrated digital signals through a single-wire interface and connecting to the main controller's GPIO port, avoiding complex AD conversion circuits and reducing signal interference. GY-30 digital light intensity module is used for illumination detection, connecting to the main controller via I2C interface, with spectral response characteristics close to the human eye, capable of outputting accurate illumination values in real time without additional signal conditioning. MQ-2 semiconductor gas sensor is selected for smoke detection, whose analog output is connected to the main controller's ADC port, converting smoke concentration changes into voltage signal changes to realize quantitative smoke concentration detection through the main controller's AD conversion. HC-SR501 human body infrared induction module is applied for infrared intrusion detection, connected to the main controller's GPIO port and set to repeat trigger mode, which can capture infrared signal changes of human movement in real time and output high-level signals to the main controller when intrusion behavior is detected, with a detection range of 120° cone angle and 7 meters, meeting the laboratory's security detection needs.

Table 1 Key Parameters of Core Detection Sensors

Sensor Type	Model	Core Parameter	Interface Type	Working Voltage
Temperature & Humidity	DHT11	Temp: 0~50℃,	GPIO	3.3V~5V
Illumination	GY-30	0~65535 lx	I2C	3.3V~5V
Smoke Detection	MQ-2	Flammable gas	ADC	5V
Infrared Intrusion	HC-SR501	120 °detection angle	GPIO	3.3V~5V

5. Conclusion and Outlook

This paper designs and implements an intelligent laboratory monitoring system with STM32F103C8T6 as the core, aiming at the problems of slow response, supervision blind spots and incomplete data in traditional university laboratory safety management relying on manual inspection. The system adopts modular and three-layer architecture design, integrates multi-sensor detection, on-site display, acousto-optic alarm and wireless cloud communication functions, realizes real-time collection and local processing of laboratory environmental and security parameters as well as remote visual supervision, and physical tests verify that the system runs stably with high data accuracy and fast abnormal response speed[1], which effectively makes up for the defects of traditional management mode, upgrades laboratory safety management from passive post-processing to active pre-warning, and improves the intelligent protection level and management efficiency of laboratories with low cost and strong practicability. For the future research and optimization direction, the system can be further expanded by introducing video monitoring and multi-gas precision detection modules to enrich the monitoring dimensions and improve the accuracy of hazard judgment; it can also realize the linkage control with laboratory intelligent equipment such as ventilation fans and fire extinguishers to form a closed-loop system of "detection-warning-disposal"; in addition, the big data analysis function can be added on the cloud platform to mine the change law of laboratory environmental parameters and realize the predictive early warning of potential safety hazards, so as to further improve the intelligence and automation level of the system and provide more comprehensive technical support for the intelligent construction of university laboratories.

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