Real-Time Laboratory Security Alert System based on Adaptive Multi-Source Data Fusion

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ABSTRACT

There are potential safety hazards in the laboratory such as unauthorized access, and abnormal temperature and humidity fluctuation. These risks pose significant threats to the safe storage of chemical reagents, the proper operation of precision instruments, and the overall security of laboratory assets. Traditional manual inspection methods often fail to provide timely monitoring of these critical aspects, leaving room for undetected incidents. To address these challenges, with the aid of WiFi communication to intelligently supervise the laboratory environment, a sophisticated laboratory security warning system based on the core control chip of STM32F103RCT6 as well as integrated various sensors has been developed. Meanwhile, we design fuzzy logic fusion weighted method to fuse multi-source data into a unified warning value to decide whether to trigger an alarm. As soon as the system detects any anomalies, it immediately triggers an audible alarm and simultaneously uploads the relevant data to the China Mobile OneNet IoT cloud platform. This advanced system offers comprehensive data management capabilities, including storage, query, and export functions. By providing real-time monitoring and rapid alerting, it effectively identifies potential risks, significantly reducing the likelihood of accidents. Furthermore, it enhances management efficiency and emergency response capabilities, thereby ensuring the safety and security of laboratory operations.

General Terms

Embedded Software Development

Keywords

Laboratory environment warning system; Sensors; STM32; WiFi communication

1. INTRODUCTION

Laboratory environment is usually complex due to various experimental devices, frequent and chaotic personnel activities. Once the fire, theft and other accidents broke out in the case of chemical reagents, precision instruments in the laboratory will cause huge losses and threaten to the safety of personnel. Therefore, the issue of laboratory safety become more and more important in recent years. It is crucial to conduct the study of intelligent laboratory safety warning system. The rapid development of Internet of Things (IoT) technology and communication technology has provided technical possibilities for improving intelligent monitoring environment warning laboratory. In light of this, an intelligent monitor system to facilitate laboratory management has been designed. It is developed on STM32F103RCT6 combined various detection modules such as smoke, flame, and human body detection aid with WiFi communication technology[1-2]. It can monitor the safety condition of laboratories in real time, quickly discover accidents and carry out alarms so as to reduce the losses. Meanwhile, it supports data storage, query, export and visualization display to enhance the efficiency of laboratory personnel management. In addition, this system is based on WiFi communication and battery power supply, which has the advantages of flexible installation, high reliability and easy deployment.

2. OVERALL SYSTEM DESIGN

The system overall consists of the main control chip and peripheral power supply circuit and sensor module. It realizes the functions of smoke detection, temperature and humidity detection, flame detection, human body detection and abnormal alarm. It consists of Microcontroller module,various sensor modules[3-6], such as DHT11, MQ-2 to monitor environmental parameters and convert them into electrical signals. ESP8266 module is employed to realize wireless data transmission supported by a variety of communication protocols, and real-time data can be uploaded to the server and receive instructions. Alarm module includes audible and visual alarms that can be sounded locally and notified to managers remotely via WiFi module[7]. Power supply module equipped with a backup battery to ensure that the system can still operate normally in the event of a power failure. Figure1 shows the overall system design block diagram.

2.1 Hardware Design and Implementation

Hardware selection and design are key in the design of laboratory safety warning system based on WiFi communication. The system adopts STM32F103RCT6 as the core control chip with high performance, low power consumption and rich peripheral interfaces, which can efficiently handle data acquisition, signal processing and communication tasks. The sensor module includes MQ2, DHT11, which have high precision and high sensitivity and can accurately collect environmental data. The communication module uses ESP8266-WiFi, which has low power consumption and stable transmission to ensure real-time data uploading to the server[8]. The system is designed with dual power supply mode (mains power and backup lithium battery) to enhance reliability. The hardware design considers modularization and expandability, which is convenient for upgrading and maintenance, and ensures the long-term stable operation of the system.

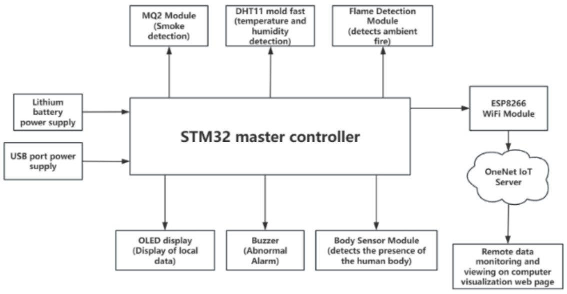

Fig 1: The schematic diagram of the overall system design

1. Main control module

The main control module adopts STM32F103RCT6 chip with high performance, low power consumption and rich peripheral interfaces[9]. The chip includes 48 KB SRAM, 256 KB Flash, multiple timers, 51 general-purpose IO ports, five serial ports, two DMA controllers, three SPI interfaces, two single-bus interfaces, one USB interface, one CAN interface, three12-bit ADC, one 12-bit DAC and one SDIO interface. The development board comes with a 1.4-inch TFT-LCD color screen, which can display sensor data and operation status information. The core control module is responsible for the overall control and coordination of the system, collecting data such as temperature and humidity, smoke concentration, flame signals, human activity, etc., and connecting to the WiFi communication module through the UART interface to realize the data remote transmission and alarm function[10]. The schematic diagram of the STM32RCT6 minimum system board is shown in Figure 2.

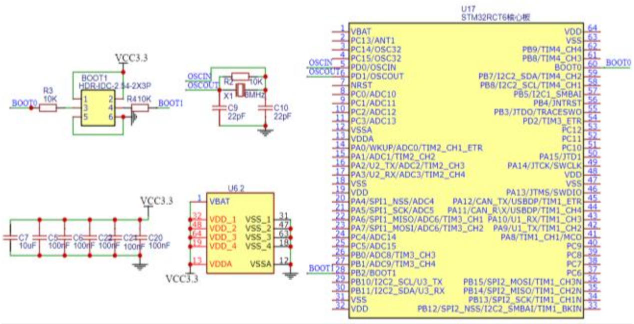

Fig 2: STM32RCT6 minimum system board schematic

2. Power Supply Module

The module of Power supply is the focus of the laboratory safety warning system, which provides stable and reliable power support for the system. The module supports lithium battery power supply and USB interface power supply, which can be flexibly switched according to the actual use scenarios. The lithium battery is suitable for scenarios where there is no external power supply or mobile deployment is required, ensuring that the system can still operate normally in the event of an unexpected power outage, while the USB interface power supply is convenient for directly connecting to the power adapter, providing stable power input for the system and charging the lithium battery at the same time. This dual power supply mode improves the adaptability and service life of the system, providing a solid power protection for the system. Figure3 shows the schematic diagram of the power supply module.

3. Temperature and humidity module

The temperature and humidity module adopts DHT11 digital temperature and humidity sensor, which is characterized by high reliability, good stability, low cost, fast response and strong anti-interference ability. The sensor includes capacitive moisture-sensing element and NTC temperature measurement element, connected to a high-performance 8-bit microcontroller. The module monitors the temperature and humidity in the lab in real time and uploads the data to the cloud platform through the WiFi communication module. The laboratory has strict environmental requirements, the module can detect abnormal temperature and humidity in time to prevent affecting the experimental results or equipment damage. Figure 4 shows the schematic diagram of DHT11 digital temperature and humidity sensor.

4. Smoke Sensing Module

The module of Smoke sensing adopts MQ2 smoke sensor, based on semiconductor gas-sensitive material, the core sensitive element is tin dioxide (SnO_2). The internal heater of the sensor heats the sensitive element to 200-300 degrees Celsius. When combustible gas or smoke exists in the environment, the gas molecules adsorb onto the heated surface of the tin dioxide, triggering a chemical reaction that leads to a change in the conductivity of the material, thus altering the resistance value. The module warns of accidental disasters by detecting the concentration of smoke in the air, and once the concentration exceeds the standard, the system immediately triggers an alarm and notifies the relevant personnel through the WiFi communication module. The schematic diagram is shown in Figure5.

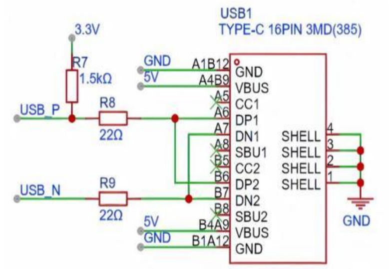

Fig 3: Schematic diagram of power supply

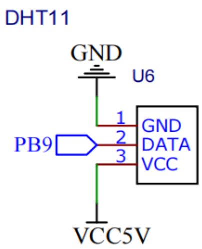

Fig 4: Schematic diagram of DHT11

5. Flame detection module

Flame detection module is based on optical detection technology, the flame burning emits a specific wavelength of infrared light (760nm-1100nm), which is detected by the infrared photoelectric diode and converted into an electrical signal. When the light intensity exceeds the preset threshold, the module outputs a low-level signal, while the analog output pin outputs a voltage value proportional to the flame intensity. The module is connected to the main control chip, triggering the sound and light alarm device when the flame is detected, and uploading the alarm information to the cloud platform through the WiFi module. As shown in Figure 6 is the schematic diagram of the flame detection module.

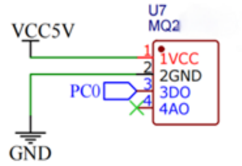

Fig.5: Schematic diagram of MQ2 smoke sensor

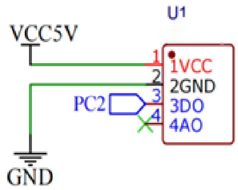

Fig 6: Schematic diagram of flame detection module

6. Human detection module

The human body detection module is based on the infrared pyroelectric effect, in which the human body, whose temperature is higher than that of the surrounding environment, emits infrared rays of a specific wavelength. When the human body enters the detection area, the infrared pyroelectric sensor (PIR) in the module senses the infrared changes and converts them into electrical signals. The module amplifies and filters the pulse signal through a signal processing circuit to determine whether there is human movement. The module monitors the activity status of people in the laboratory in real time, realizes safety warning and management, and triggers alarms or takes safety measures when necessary. Figure 7 shows the schematic diagram of the human body detection module.

7. Display Module

The display module adopts 0.96-inch OLED, which is connected to the main control chip through 7-pin SPI interface. The module shows real-time environmental data collected by the sensor and alarm information to help laboratory personnel visualize the current environmental status. The display is characterized by self-illumination, high contrast, low power consumption, fast response speed, etc., and is able to present information clearly under different lighting conditions. Figure 8 shows the schematic diagram of OLED.

8. WiFi communication module

WiFi communication module adopts ESP8266 to realize wireless network connection and data transmission. The module supports a variety of communication protocols, connects with the main control chip via serial port or SPI interface, receives sensor data and encapsulates it into TCP/IP packets, and uploads it to the cloud server or local monitoring platform via WiFi network.ESP8266 also supports a variety of operating modes, including Station mode, Soft-AP mode and Station+Soft-AP mode, to adapt to different network environments and application scenarios. ESP8266 also supports multiple operating modes, including Station mode and Soft-AP mode, to adapt to different network environments and application scenarios. Its built-in TCP/IP protocol stack and rich AT instruction set simplify the development and debugging process. The schematic diagram of ESP8266-WiFi module is shown in Figure9.

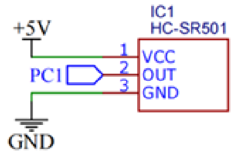

Fig. 7 Circuit schematic of the human detection module.

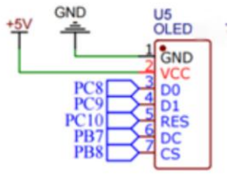

Fig 8:Circuit schematic of OLED

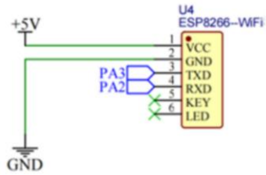

Fig 9: Circuit schematic of ESP8266

2.2 Software Design and Implementation

1. Main program design and implementation

In this system, the main program adopts a modular design and coordinates the operation of each functional module through the main program. After initialization, the timer triggers the data acquisition module to obtain environmental data such as smoke concentration, gas concentration, temperature and humidity from the sensors. These data are passed to the safety warning algorithm module for analysis and judgment. If an abnormality is detected, the main program immediately sends out a local alarm through the buzzer and uploads the alarm information to the cloud platform using the WiFi module to notify the relevant personnel to deal with it in time. At the same time, the collected data are shown on the local display in real time and uploaded to the cloud for storage and analysis, realizing the combination of local monitoring and remote management. The whole main program runs through modularized calling and cyclic operation to ensure that the system efficiently and stably completes the laboratory safety warning tasks and provides reliable guarantee for the safe operation of the laboratory. As shown in Figure10, the flow chart of the main program.

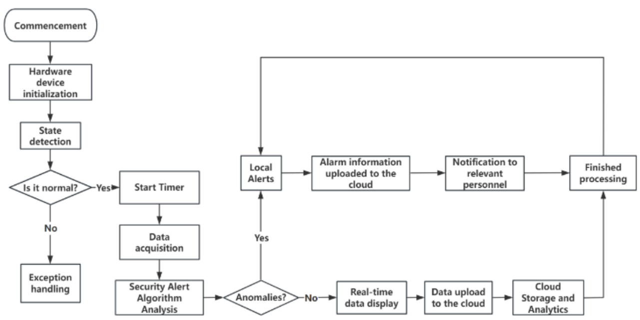

Fig 10: Flowchart of main program

2 . Design and implementation of safety warning algorithms

During constructing the laboratory safety early warning system, an accurate judgment is made by comprehensively analyzing the data from three sensors, namely smoke detection (MQ2), flame detection (Flame) and human body detection (HumanBody). The system leverages fuzzy logic fusion technology and weighted summation method to fuse the three parameters into a unified warning value to decide whether to trigger an alarm.Fig.11 shows a flowchart of the security alert algorithm.The steps of the algorithm are as follows:

Step1: Parameter quantification and standardization: quantification of smoke concentration as 0-1 (0 for no smoke, 1 for extreme danger), flame detection and human body measurements as binary signals (0 for no, 1 for yes).

Step2: Weighted assignment: Assign weights to each parameter based on safety requirements. For example, smoke is weighted at 0.5, flame at 0.3 and human detection at 0.2.

Step3: Fuzzy logic fusion: Smoke concentrations are divided into three bands (low: 0-30, medium: 31-70, high: 71-100) and assigned an affiliation (low=0.3, medium=0.6, high=1). The affiliations for flame and human detection were directly used for their binary states (yes=1, no=0).

Step4 : Risk assessment: Calculation of the composite value at risk R using the formula:

$$R = W_{sm} \times SmLevel + W_{f} \times FlameLevel + W_{hb} \times Human$$

Where SmLevel is the smoke affiliation, FlameLevel and HumanBodyLevel are the weight adjustment values for flame and human body detection, respectively.

Step5: Alarm Threshold Setting: Set the alarm threshold T (e.g. 0.5) and activate the buzzer alarm when R≥T.

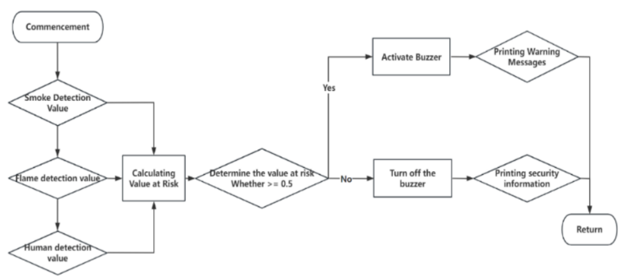

Fig 11: Flowchart of the algorithm

3.Cloud platform and client

This study chooses OneNet IoT[**Error! Reference source not found.**] cloud platform because it supports multiple network protocols (e.g., MQTT, LWM2M, HTTP, etc.), powerful device management functions, supports full lifecycle management of devices, provides efficient data storage and querying capabilities, and a variety of value-added services (e.g., location positioning, remote upgrading, message queuing, data visualization, and artificial intelligence, etc.), which also can effectively improve the development efficiency and operational stability of IoT projects[**Error! Reference source not found.**].

After registering a OneNet account, select the IoT open platform and add products, configure device information and network parameters. Upload sensor data (e.g. temperature and humidity, smoke concentration, etc.) to OneNet platform through MQTT protocol, and develop client subscription function to receive control commands and realize remote monitoring. After testing and debugging to ensure stable data upload and correct execution of commands, it successfully realizes the efficient docking between the laboratory safety warning system and the OneNet platform to meet the needs of remote monitoring and management[**Error! Reference source not found.**-15]. As shown from Figure14 to Figure 23, the device diagram, data display page diagram, device details detailed information diagram are added, respectively.

3. SYSTEM TEST

3.1 The test of Temperature and Humidity Module

A field test of the temperature and humidity module was conducted to test whether the temperature and humidity sensor would detect a change in the temperature and humidity values by blowing on it artificially. Figure 12 and Figure 13 show the temperature and humidity results detected by the DHT11 digital temperature and humidity sensor in the current environment displayed on the OLED display page, The test results show that the temperature and humidity results collected by the DHT11 digital temperature and humidity sensor can change in real time with the changes in ambient temperature and humidity, indicating that the sensor module has good responsiveness and accuracy and can work normally. Figure14 and Figure15 demonstrate the results of temperature and humidity according to the changed environmental parameters on the Cloud Platform.

Fig 12:Temperature and humidity monitoring

Fig 13: Results of changed temperature and humidity

Fig 14: The results of present temperature and humidity on the Cloud Platform

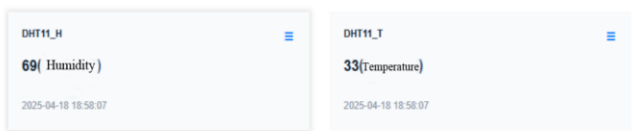

Fig 15: The results of temperature and humidity varied environment parameters on the Cloud Platform

3.2 The test of Smoke Detection Module

The smoke detection module was tested in the field and the MQ2 smoke sensor was used to simulate a scene with smoke by using a lighter to emit toxic gases. Figure16 shows the smoke sensor detects the harmful gases emitted by the lighter and the light turns green. The OLED displays the smoke alarm as shown in Figure 17. Figure18 and Figure 19 show the corresponding results on the Cloud Platform. The test results show that the sensor is able to accurately monitor the presence of smoke in the environment. The test visualizes the detection effect of the MQ2 smoke sensor and verifies that the module is in normal working condition.

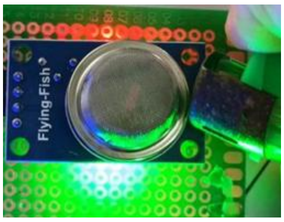

Fig 16: Harmful Gas Detection with green light

Fig 17: Smoke Detection in an Alarm state

Fig 18: Detection result of smoke on the Cloud Platform before testing

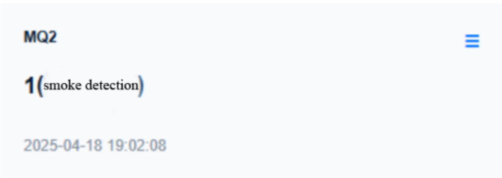

Fig 19: Detection result of smoke on the Cloud Platform after testing

3.3 The test of Flame Detection Module

The flame detection module was field tested to simulate a realistic scenario of a real fire hazard occurring through the flame of a lighter. Figure 20 shows the flame detection sensor detects the flame of the lighter lights up green .Figure 21 shows that after the sensor lights up green, the OLED display shows that the flame detection is in alarm status. Figure 22 and Figure 23 show the corresponding detection results of flame on the Cloud Platform. The test results show that the flame sensor can accurately detect the presence of flame in the environment, verifying that the flame detection module in the system is working well.

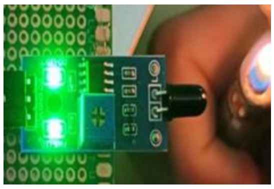

Fig 20: Flame detected with green light

Fig 21: Flame detection in an alarm condition

Fig 22: The detection result of flame on the Cloud Platform before testing

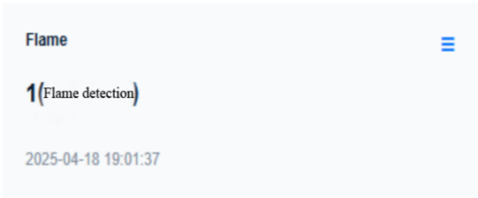

Fig 23: The detection result of flame on the Cloud Platform after testing

3.4 The test of Human Body Detection Module

A field test of the human detection module is shown in Figure 24, where the infrared pyroelectric human detection sensor lights up red when someone approaches .Figure 25 shows that after the sensor lights up red, the OLED display shows that the human detection of the system is in alarm status.Figure 26 and Figure 27show the corresponding detection results of human body, that is unauthorized access, on the Cloud Platform. The test results show that the human infrared sensor can accurately recognize whether there is someone in the current environment, and can maintain high detection accuracy under different environmental conditions. The detection effect of the sensor is demonstrated intuitively, and the normal working condition of the human infrared sensor module is verified.

Fig 24: Human detection sensor with red light

Fig 25: Display of human body detection in an alarm state

Fig 26: The detection result of unauthorized access on the Cloud Platform before testing

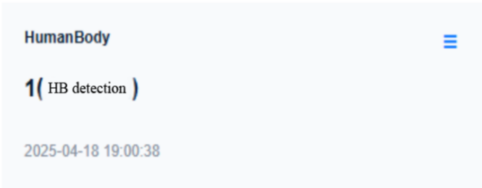

Fig 27: The detection result of unauthorized access on the Cloud Platform After testing

4. CONCLUSIONS

This paper presents the design and implementation of a WiFi-enabled laboratory safety warning system. By integrating temperature-humidity, smoke, flame, and human infrared sensors, it enables real-time monitoring of the laboratory environment and provides timely early warnings. The system is equipped with functions such as environmental parameter monitoring, abnormal alarm triggering, and remote access, effectively preventing potential accidents like fires and unauthorized intrusions and ensuring the safety of personnel and equipment. In the future, we will explore the integration of more advanced sensors aiming to improve accuracy, reliability, and expand the scope of monitored parameters. Ultimately, the system is expected to be extended to industrial, medical, and environmental protection sectors, providing safety management support across a wider range of applications.

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6. ACKNOWLEDGMENTS

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