Fire Monitoring System for Power Batteries on Ship

Lan Wei *, Zhengkang Zhou, Zhuoer Wang
School of Information Engineering Wuhan University of Technology Wuhan, China

*Corresponding author: 288489@whut.edu.cn

Abstract. In recent years, due to the influence of policies such as environmental protection and reduction of harmful gas emissions, clean energy such as lithium batteries, hydrogen-oxygen fuel cells, and waste heat power generation technologies are being applied on ships. As the application level of new energy continues to expand, its safety issues have attracted more and more attention from society. The system collects the air pressure, temperature, humidity, flame heat radiation, and smoke information inside the ship's power battery box, and uses the STM32 processor to determine whether the ship's power battery has a fire hazard. This system can effectively avoid the thermal runaway of the power battery, detect the thermal runaway at an early stage and actively respond to reduce losses, and protect the life and property safety of passengers on board.

Keywords: CAN communication, power battery, fire monitoring.

1. Introduction

The improvement of power battery technology and industrial level will quickly promote the transformation process of transportation electrification, and the development and application of electrification technology in ship transportation related fields are highly valued. In recent years, due to the influence of policies such as environmental protection and reduction of harmful gas emissions, clean energy such as lithium batteries, hydrogen-oxygen fuel cells, and waste heat power generation technologies are being applied on ships. Battery-powered ships are attracting attention because they do not emit harmful gases such as NOx, SOx, PM2.5, and greenhouse gases such as CO2, and meet increasingly standardized environmental protection requirements [1]. According to the prediction of relevant agencies, the global pure electric and hybrid electric boat market will rapidly exceed 20 billion US dollars in 2027 [2]. However, marine power battery technology is currently facing serious safety issues that may arise, led by thermal runaway. Lithium batteries are safe under normal circumstances, and the environmental temperature, charging and discharging system, storage time, etc. of the battery application will have a significant impact on battery safety, and battery abuse is the main factor causing safety risks [3].

In view of the above situation, how to improve the safety protection measures of the ship's power battery is an urgent problem in the development process of the power battery ship. Therefore, this paper designs a ship power battery fire monitoring system based on STM32, which has the function of real-time monitoring of temperature, humidity, air pressure, smoke, and flame conditions in the battery box.
2. The Hardware Design of the System

Figure 1 is a structural block diagram of a power battery fire monitoring system based on STM32, which consists of a main control chip, temperature detection module, humidity detection module, air pressure detection module, smoke detection module, flame sensor module, alarm module and communication module. The main control chip of this system is STM32F103VET6 chip, which has 1 CAN2.0, 3 ADCs, 8 timers, and 3 serial modules, which can meet the system requirements in performance. The main control module receives the data of each sensor through the CAN bus, and then instructs the alarm module to work and provides fault location information after risk judgment.

![System structure block diagram](image)

**Figure 1.** System structure block diagram

2.1. The Concept of Large-scale Network

According to the functional requirements of the system, the main control chip needs to receive and process the data information collected by multiple sensors. By analyzing the functional requirements of the system, the main control chip needs to receive CAN messages from multiple slave modules and process the messages. It is forwarded to the CAN network of the whole ship, so the main control chip needs to have 2 CAN communication functions. When there is an alarm message, it is necessary to drive the work of multiple peripherals according to a certain control strategy, and the main control chip needs to have multiple IO ports and multiple interrupts. In combination with the working conditions, the main control chip is designed to use STM32F103VET6. STM32F103VET6 The enhanced series requires a voltage range between 2.0V-3.6V and can operate at a temperature of -40°C to +105°C, and this system can turn on a power saving mode to adapt to the power consumption of some low-power applications. The enhanced series contains standard communication interfaces: 3 USARTs and 2 I2C and SPI, and also contains 1 PWM timer, 2 12-bit ADCs and 3 general-purpose 16-bit timers to meet the control needs of multiple coprocessors.

2.2. The Survivability Structure Model of Large-scale Network

The system monitors the real-time parameters and their change values of the detection points of CO gas, smoke, temperature and flame inside the battery box, uses the data monitoring model to dynamically analyze and process the parameter changes, and intelligently judges whether there is a risk of thermal runaway fire. When the power battery fails and begins to release pressure, heat, etc., the detector can detect abnormal changes, and send out early warning signals to the cockpit through the CAN bus or the wiring harness during the potential phase, smoke phase, high temperature phase, and open flame phase of the fire. Realize hierarchical early warning and control activation of fire extinguishing devices to maximize the safety of battery packs. The specific sensor function design is as follows.

(1) Sensor information collection and processing

The control system needs to collect and process the humidity, smoke (gas), temperature, pressure, and flame information in the power battery, and perform different processing according to the different processing types of sensor information. If the processing type is analog, consider whether an amplifying circuit or peripheral circuit is needed to make the output within the acquisition range based on the output.
voltage. If the processing type is digital, you can use a comparator circuit or directly connect to the input and output ports of the MCU (i.e. STM32) to judge.

(2) Sensor configuration
Temperature sensor: Each power battery box uses a temperature sensor. There are three levels of alarms based on the threshold, and the sensor is directly connected to the GPIO port.

Pressure sensor: Because the box is in a sealed isobaric environment, only one set of pressure sensors is needed. According to the threshold value, there are three levels of alarm, and the sensor is connected to the GPIO port through the drive circuit.

Humidity sensor: Because the inside of the box is a sealed environment, only one set of sensors is required to be placed at the bottom of the power battery box, which mainly detects whether the box has entered water or is damp. According to the threshold value, the alarm is divided into two levels, and the sensor is connected to the GPIO port with ADC through the driving circuit.

Smoke sensor: Considering that there is a certain error in this sensor, it is planned to use two sets of smoke sensors, one of which is a redundant configuration and also participates in the work. The sensor is directly connected to the GPIO port.

Flame sensor: Considering the urgency of the fire, the flame sensor detects a specific wavelength of visible light, and plans to use two sets of flame sensors as redundant backups for each other, and the sensors are directly connected to the GPIO port.

In this design, the control system and the sensor system communicate through the CAN bus. The mainstream independent CAN protocol control chips that meet the requirements on the market are MCP2515 and SJA1000. Combining the existing resources to compare and test the two chips, the hardware circuit of MCP2515 is found to be more complicated in the process of building the hardware circuit test, but the program requires less resources for the single-chip microcomputer. Under the comprehensive comparison, the MCP2515 CAN controller and CAN module circuit are selected. Also need to add CAN transceiver TJA1050 and related hardware circuits. In addition, this design simulates the ship’s CAN network. After verification, the CAN module is compatible with the ship’s CAN network.

The CAN controller has the problem of baud rate matching, and all devices on the CAN bus must use the same baud rate. However, not all devices require the same main oscillator clock frequency. For devices with different clock frequencies, the bit rate should be adjusted by appropriately setting the baud rate prescaler ratio and the number of time shares in each time period. The concept of bit time is introduced here. Bit time represents the time required for a binary bit to be transmitted on the bus. In the bit timing of CAN, the bit time is divided into four sections: synchronization section, propagation section, phase buffer section PS1, phase buffer section PS2, the specific bit time formula is shown below.

\[
T_{bit} = \text{synchronization segment} + \text{propagation segment} + \text{phase buffer segment PS1} + \text{phase buffer segment PS2}
\]

These segments are all units of time share TQ. The CAN clock is a time length value divided by the system clock, which is actually a time share. The bit time has a total of 8-25 time shares.

\[
TQ = 2 \times BRP \times T_{osc}
\]

The single-chip and MCP2515 crystal oscillators are different. If they communicate with each other, the baud rate needs to be adjusted and matched. The specific protocol is introduced in the software design part. The communication between two CAN modules of the same baud rate in this design can be configured according to the chip manual. The schematic diagram of CAN communication module circuit is shown as in Fig. 2.
In summary, the control system has a pathless sensor interface, CAN controller, main control chip STM32, dedicated power supply circuit, storage circuit, expansion IO port and corresponding TTL circuit on the hardware circuit. The final design circuit function diagram of the control system is shown in Figure 10. The display module and the wireless module can be connected to the serial port. The above content has been calculated for the MCU's computational requirements for processing its data. The computational capacity of the 32-bit microcontroller STM32F103 meets the requirements and has certain redundancy. The complete circuit schematic diagram of the control system is shown in Figure 3.

![Figure 3. Schematic diagram of the complete circuit of the control system](image3)

3. Software function design
The idea of this part is to judge whether the most advanced fault condition is satisfied, and if it is satisfied, judge whether the time since the last fault transmission exceeds 30 seconds. If it exceeds and no treatment measures are taken, it is judged whether the ship is moving. If it is, the operation console screen is activated to display warning, and the alarm module realizes sound and light alarm. If it is docked, the wireless module is activated to transmit information to the command center and the person in charge of the ship. The information includes detailed identity information and latitude and longitude location information, and it is connected to the fire fighting system to take active measures to extinguish the fire; if the time since the last failure is not sent After 30 seconds or there is a command reply, it is determined that the fault is eliminated and the alarm is stopped to save the fault information. If the MCU judges that the sensor data does not meet the highest-level fault condition, it judges whether the second-level fault condition is met, and if it is satisfied, it judges whether the time since the last fault transmission exceeds 30 seconds. If it exceeds and no treatment measures are carried out, judge whether the ship is moving. If it is, start the operation console screen to display the corresponding secondary
warning, the alarm module realizes sound and light alarm, and access the fire fighting system to take active measures to extinguish the fire.

If it is docked, the wireless module is activated to transmit information to the command center and the person in charge of the ship. The information includes detailed identity information and latitude and longitude location information. It also accesses the fire fighting system to take active measures to extinguish the fire; if the time since the last failure was sent is not more than 30 seconds or if there is a command reply, it will be determined that the fault is eliminated, stop the alarm, and record the fault information.

If the third-level failure (hidden hazard) condition is met, it will continue to judge whether the time from the last failure is more than 40 seconds. If it exceeds 40 seconds and there is no response to eliminate the failure, the hidden danger will continue to be displayed, and the failure information will be uploaded to the command center and ship responsibility People, the process ends.

The system starts self-check after power on, and reads sensor information from each control system after the self-check passes. The detailed process is shown in Figure 4. Since STM32 is a microcontroller, it can only read each sensor hung on the bus in turn.

The core algorithm of the system is the multi-sensor weight distribution algorithm. The core idea is to use a certain threshold to determine the fault level, and use the equation to fit each fault level. If the fit degree exceeds 80%, it is considered to be in line with this fault level. When confirming the level, a series of unbiased estimators are calculated, and the greedy algorithm, Proportional integral algorithm etc. ensure the stability and accuracy of system fault judgment.

The weight distribution algorithm is based on the weighted optimal weight equation, which is derived as follows:

\[ x(k) = ^\mathbf{\hat{x}}(k) + C(k) \]

Where \( x(k) \) is the measured value of a certain sensor at a certain moment, \(^\mathbf{\hat{x}}(k)\) is the real value measured at the moment of a certain test parameter \( k \), and \( C(k) \) is its error value. (The value should be selected according to the actual data here. The following is a Gaussian white noise with zero mean and variance \( \sigma^2 \) for the convenience of calculation.)
If in the process of data fusion of n sensors, the weight of the i-th sensor is $B_i$, the fusion result is
\[ y(k) = \sum B_i \cdot x_i(k), \quad E[(r - y)^2] = \sum B_i^2 \cdot \sigma_i^2, \]
Through the Lagrangian multiplier method, the optimal weight of the sensor can be obtained as
\[ B_i = \left( \frac{1}{\sigma_i^2} \right) / \sum \left( \frac{1}{\sigma_j^2} \right). \]
In practice, because of various interferences, it is necessary to introduce the
\[ D(k), \quad x(k) = \lambda x(k) + D(k) + C(k), \]
the calculation process is as above, which is omitted here.

The subsequent processing process can be simply arranged in time sequence. The initialization, reading, and use procedures of each module are all associated with the GPIO port of STM32, which has been packaged and will be omitted here.

The core of the greedy algorithm is that it does not consider the overall optimization, and only makes a local optimal solution in a certain sense. This algorithm will consider the sensor damage problem to avoid fire, but it is not given due to the damage of some sensors. Fire alarm.

The core of the proportional-integral algorithm is that the output signal $c(t)$ of the microcontroller simultaneously proportionally reflects the integral of the input signal $\varepsilon(t)$ and the input signal $\varepsilon(t)$. This algorithm is generally used for the stable control of motors and other systems. The proportional integral algorithm focuses on the steady-state control of the system, and has the characteristics of high steady-state accuracy and fast dynamic response. This algorithm is introduced in this design so that the system can stably control the ship's fire-fighting system and alarm system through the CAN bus. Taking into account the characteristics of the ship's fire and alarm systems that need to provide stable control signals, the specific function of introducing the proportional integral algorithm is that the control signals will not be changed due to part of the system hardware damage and fire changes.

4. System test

The important goal of the system testing project is to test the fire monitoring system of the ship's power battery. The test not only requires functional testing of important functional modules, but also includes the stability and reliability of the overall system. The official version also needs to be on the ship. For actual function testing, it should focus on whether the system performance and function can meet the real expectations of customers.

The test condition is to simulate the storage of the power battery compartment on the ship in the waters, and the fault simulation uses the battery liquid inside the power battery (the current choice is a variety of lithium-ion battery mixtures) and the combustion of chemical substances in the casing. The test indexes of each module of the specific system are shown in Table 1.

| Equipment name         | Description                                                                 |
|------------------------|-----------------------------------------------------------------------------|
| Communication module   | Signal strength, accuracy of information,                                    |
| Control module         | Detection and analysis of five types of sensor information, stability of CAN |
| Functional module      | Stability of wired/wireless communication with control module, reliability of |
| Display screen         | The screen is connected to the serial port hardware of the control system, and |
| Sensor module          | Continuous and independent environmental information monitoring, stability of |

The test indicators of the sensor part according to the requirements are shown in Table 2. According to the actual situation and subsequent time calculation, the reaction time of each sensor must be less than 10ms, and there should be no false triggers caused by circuit errors.
Table 2 Sensor information collection function test table

| Serial number | Test function       | Test content                                                                 |
|---------------|---------------------|------------------------------------------------------------------------------|
| 1             | Temperature collection | After the temperature sensor module is connected to the slave control system, it can collect the temperature value of the system more accurately and sensitively by comparing with the handheld electronic thermometer. |
| 2             | Humidity collection  | Humidity collection is a digital signal output, spraying water mist 10cm around the humidity sensor, the sensor can be triggered quickly, and the threshold is effective and controllable. |
| 3             | Pressure collection  | This test is compared with a pressure gauge. Under a certain pressure, an obvious signal can appear. |
| 4             | Gas collection       | During the test, ignite the mixture of 10ml battery fluid and plastic, and ignite at a distance of 50cm from the sensor. When the rubber has dense smoke, the smoke sensor needs to output information. |
| 5             | Flame collection     | During the test, the mixture of 10ml battery liquid and plastic is ignited, and it is ignited at a distance of 60cm from the flame sensor. The sensor is triggered during the ignition process, and the structure is effective and sensitive. |

The test indicators implemented by the system function are that the display and communication modules are normal. The specific test indicators are shown in Table 3. Each function also needs to test the termination process after manual response, and the response time of each module should be less than 30 seconds.

Table 3 Function module detection

| order | performance                      | Test items                                                                 |
|-------|----------------------------------|-----------------------------------------------------------------------------|
| 1     | Information upload               | After the control system confirms the fault, it activates the wireless communication module to send information to the designated terminal according to the designated data format, and informs the current fault type and the battery box number where the fault is located. The content sent is different according to the severity of the alarm level, and the information is updated in real time according to the fault. |
| 2     | Wireless sound and light alarm   | In the case of no response from the CAN bus, the wireless module is activated and linked to the ship’s sound and light alarm system to give an alarm. |
| 3     | Whole ship control access        | After the control system confirms the fault, the hull fire-fighting system is connected via CAN to actively suppress the fire. |
| 4     | Screen display and sound and light alarm | The main control system can start the serial screen to display specific alarm information when there is alarm information, and play different frequency alarm information according to the severity of the alarm level. |

The design of this article passed the above test and reached the expected index. The main control circuit PCB design diagram of this design is shown in Figure 5.
5. Summary

This design meets the requirements for detecting ship power battery fire at this stage, and guarantees the safe charging process of ship power battery. Introduce ship CAN bus communication technology and information transmission technology, select sensors for the constituent materials of lithium-ion batteries, configure multiple sensors according to specific ship power battery boxes, and introduce multi-source information judgment mechanism and sensor redundant configuration according to ship-related safety indicators. Make the false alarm rate as low as possible. The introduction of this system in the new lithium-ion battery box can be combined with the safety measures inside the battery to become a reliable safety line of defense, laying the foundation for the mass production of more efficient power batteries, which will also be the future development direction of power batteries.

References

[1] Qin Qi and Wang Youzhen, "Global New Energy (Clean) Ships and Related Intelligent Technology Development," Ships, vol. 29, pp. 29-41, 2018.

[2] Fan Wei, Wang Jing and Feng Shuhuan, "Development of Marine Battery Power Technology," China Shipbuilding Survey, pp. 66-69, 2020.

[3] Yu Quanhu, "Analysis on the Development of Power Lithium Batteries and Electric Propulsion Ships," Transportation Energy Conservation and Environmental Protection, vol. 16, pp. 29-35, 2020.