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Early LSTM-Based Early Warning System for Thermal Runaway of Lithium-Ion Batteries Using an ESP32-S3 Edge Computing Platform

Haojie Ma, Yichi Zhang, Junhao Liang, Zhichao Zhang*
North China University of Science and Technology, Tangshan, China
**Corresponding Author*

Abstract: An early warning system for lithium battery thermal runaway during charging, designed as an independent external device for new energy vehicles, electric bicycles, and portable energy storage devices. The system integrates DS18B20 temperature sensors and three-in-one gas concentration sensors (CH_4, CO, C_2H_4) to capture multi-source data. An LSTM (Long Short-Term Memory) time-series prediction model is deployed on an ESP32-S3 microcontroller using edge computing, enabling real-time trend prediction of temperature and characteristic gas concentrations several minutes in advance. Compared to traditional threshold-based Battery Management Systems (BMS), this approach shifts from post-accident alarms to pre-accident prevention, significantly improving early detection accuracy and reducing false alarms. The device features independent power supply, wireless communication (Wi-Fi/Bluetooth), and a mobile app for real-time monitoring and alerts. With low cost (basic version under 100 RMB), easy installation, and broad compatibility, the product fills a market gap for consumer-grade thermal runaway warning solutions. Experimental results show millisecond-level inference latency and reliable early warning capability, offering strong potential for large-scale adoption and enhanced lithium battery charging safety.

Keywords: Lithium Battery; LSTM; ESP32

1. Introduction

In recent years, new energy vehicles and energy storage stations develop fast. Also, consumer electronics are widely used. So application of lithium batteries is expanding. At the same time, thermal runaway causes many fire accidents. This has become a major safety concern. In fact, Fire and Rescue Department of the Ministry of Emergency Management released statistics and it shows that the number of fire accidents from lithium battery thermal runaway in 2023 can increase more than 20% compared to 2022 and the charging process is a high-incidence phase. Against this backdrop, we should develop a device that can provide early warning of spontaneous combustion risks during lithium battery charging. This has significant social value and market potential.

2. Domestic and International Market Analysis

At technical research level, we study the thermal runaway warning for lithium batteries. Current research focuses on several parts. First, many researchers try to expand Battery Management System (BMS) functions. Existing commercial BMS can monitor voltage, current and temperature, but monitoring of characteristic gases (such as CO, H_2) released before thermal runaway is not standard in most systems. Second, multi-sensor fusion technology is studied. Academic studies show that combining battery surface temperature and characteristic gas concentration can advance the warning time by several minutes. It is worth noting that machine learning-based prediction algorithms also attract much attention. In recent years, time-series prediction models such as LSTM and Transformer show good application potential in lithium battery state assessment and they become a popular research direction.

In industry, we can see that there is no mature product for spontaneous combustion warning in lithium battery charging scenarios in local market. Some new energy vehicle and energy storage companies have added thermal runaway warning functions to their BMS, but most use threshold-triggered mechanisms, making ithard to predict early thermal runaway trends. In charging process, users can be far from the battery, and only relying on thevehicle's or energy storage system's own protection mechanisms makes it hard to give warnings in time.

We design a warning device for lithium battery charging spontaneous combustion using LSTM algorithm. The device can collect battery internal temperature and gas concentration data during charging process and it uses deep learning model to predict the trend in next few minutes and then the results are compared with safety thresholds so that dangerous situations can be found early before spontaneous combustion happens. In fact, this method can help improve the safety. This solution uses multi-source sensing technology and time-series prediction algorithms. It has fast response speed and the prediction accuracy is high with low false alarm rate. So it can avoid the shortcomings of existing technologies in early thermal runaway warning and has good market competitiveness. The system can be promoted in industry.

3. Product Usage and Functions

During charging process of lithium battery, internal short circuit and overcharging can happen. Also mechanical damage may occur. These problems can trigger thermal runaway, which leads to spontaneous combustion or explosion. Femande.S et al. [1] examined the gas evolution behavior in lithium-ion batteries during thermal runaway. They studied abusive conditions like overcharging and overheating. Nebiker et al. [2]used a photoacoustic device to analyze gas products, and results show it can detect CO and CO_2 concentrations. Ohsaki et al. [3] analyzed gas components from positive electrode of lithium-ion batteries under thermal runaway conditions, and results indicate the main components include CO andCO_2, and there is also a small amount of CH_4. Wang Chunli et al. [4] sampled and analyzed gases generated in thermal runaway process of lithium-ion batteries. Before safety valve burst, gas concentration increased and CO has the highest change rate among all gases. Wang Mingmin et al. [5] conducted overcharge experiments on soft-pack and hard-case lithium iron phosphate batteries to study gases produced during thermal runaway. In early stage of thermal runaway, main gases generated are CO_2, CO, H_2 and HF. Among them, CO_2 and CO concentrations changed significantly, and H_2 also changed a lot. If abnormal temperature and gas changes can be captured early and warnings are issued, users can have time to take action. In fact, this is why we develop this product.

This device is independent external warning system for lithium battery thermal runaway in charging and discharging. It can be used in new energy vehicles, electric bicycles, as well as portable energy storage devices. In real time, it monitors battery surface temperature and ambient characteristic gas concentration. It is worth noting that we use LSTM time-series prediction to predict trends over next few minutes, and when predicted values approach or exceed safety thresholds, the system can warn users immediately so they have time to take measures.

4. Technical Implementation

(1) The measurement principle

In fact, early warning of lithium battery thermal runaway requires us to capture the dynamic changes in battery surface temperature and characteristic gas concentrations, and this is the key point in our monitoring system design. We use CH_4 and CO as indicators, and C_2H_4 is included. Then together with temperature trends we can construct a LSTM time-series prediction model that is expected to help judge the risk at early stage.

We use DS18B20 digital temperature sensor to do temperature measurement. This sensor is produced by Dallas Semiconductor. It can read temperature data and we can program it for 9-12 bit digital readout. Information from DS18B20 is read via single-wire interface. In fact, the power for temperature conversion comes from the data bus and it can also power the connected DS18B20 so we do not need additional power supply. The sensor has good performance in accuracy, conversion time, transmission distance and resolution. It can work well in complex environment during lithium battery charging.

We use a three-in-one gas concentration sensor for CO, CH_4 and etc. When thermal runaway happens, chemical reactions inside battery can release characteristic gases. We monitor these gas concentration changes. In fact, sharp temperature changes should also be monitored. Then the early dangerous signals of thermal runaway can be captured.

(2) The working principle

Sensors collect real-time temperature and concentrations of methane, CO, and ethylene during battery charging/discharging. Data is transmitted to the ESP32-S3 microcontroller via I2C/SPI interface at a sampling rate of 0.5Hz. The microcontroller embeds an LSTM-based time-series prediction model to perform real-time analysis and trend prediction.

With memory cells and gating mechanisms, it can capture long-term dependencies. In fact, we apply it to temperature and gas concentration data and the change patterns during thermal runaway can be learned because the model has memory cells that can remember history information for a long time. Compared with traditional threshold methods, LSTM model identifies subtle data trends and early prediction can be achieved.

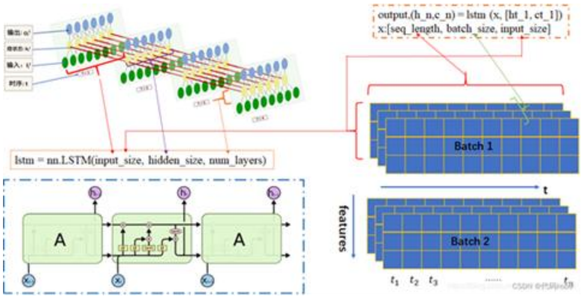

Figure 1. LSTM Prediction Flowchart

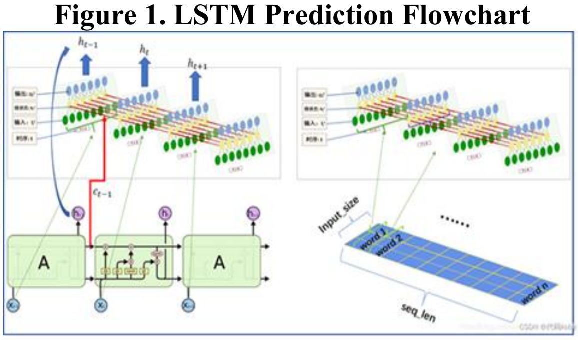

Figure 2. LSTM Prediction Flowchart

(3) The edge computing platform

We use ESP32-S3 microcontroller as edge computing core. This chip is based on Xtensa® 32-bit LX7 dual-core processor with main frequency up to 240MHz, and it has 512KB SRAM that can be expanded with external PSRAM, so the computing power and peripheral interfaces are sufficient. In fact, the microcontroller runs FreeRTOS real-time operating system. Multi-task scheduling is used here. Sensor data acquisition and LSTM model inference are processed in parallel and warning judgment is handled at the same time, so the real-time performance is expected to be good and the system should be reliable.

To make the LSTM model work on embedded platforms with limited resources, we use quantization and lightweight methods to change the trained model so it fits microcontroller deployment. Also, CMSIS-NN library is used to speed up the calculation. Test results show that one inference can be finished within 50 ms. This meets the millisecond-level warning response requirement. In fact, the warning can be real-time.

(4) The system communication scheme

The system adopts a multi-level communication architecture to achieve a complete data transmission link from acquisition to user.

a. Sensor to microcontroller communication

Uses I2C/SPI bus interfaces for high-frequency acquisition of temperature and gas sensor data, with a sampling rate of 0.5Hz, ensuring data real-time and integrity.

b. Microcontroller terminal communication

We use Wi-Fi or Bluetooth module to push warning information to mobile app in real time. Users can view real-time data and history records in the app, and warning information can also be checked there, so we can achieve full monitoring during charging process.

c. Cloud data storage (optional)

In value-added service mode, data can be uploaded to cloud servers for long-term storage, multi-device collaborative management, and personalized warning strategy customization.

(5) The overall system solution

Below is the overall architecture of lithium battery charging spontaneous combustion warning system. It is worth noting that the system includes four main parts: sensing acquisition module, edge computing module, warning output module, and user interaction module:

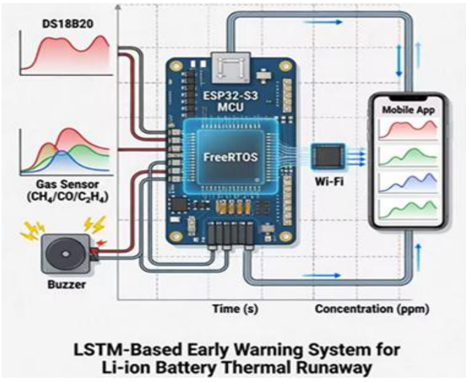

Figure 3. System Overall Framework Diagram

a. Sensing acquisition module

Composed of DS18B20 temperature sensor and three-in-one gas concentration sensor, responsible for collecting battery surface temperature and concentrations of CH_4, CO, and C_2H_4.

Figure 4. Sensing Acquisition Module

b. Edge computing module

Centered on the ESP32-S3 microcontroller, embedding FreeRTOS real-time operating system and LSTM time-series prediction model, responsible for real-time data processing and trend prediction.

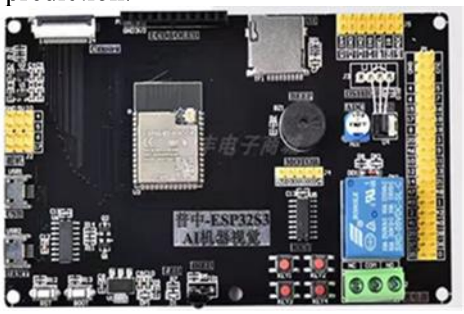

Figure 5. Edge Computing Module

c. Warning output module

Includes local buzzer and wireless communication module. When thermal runaway risk is predicted, it issues audible/visual alarms and pushes warnings to users.

Figure 6. Warning Output Module

d. User interaction module

Uses a mobile app as the carrier, providing functions such as real-time data viewing, historical record query, warning information reception, and personalized parameter settings.

The system has a full chain of "data acquisition → real-time analysis → trend prediction → warning response. " By using LSTM time-series prediction model, we can judge thermal runaway risk early. It can avoid safety hazards that may cause fire accidents.

5. Key Technologies and Innovations

(1) The key technologies

a. Multi-source sensing fusion technology

We use temperature sensors and gas concentration sensors together, and we collect surface temperature and concentrations of CH_4, CO, C_2H_4 and other gases during lithium battery charging. In fact, by using multi-dimensional sensing method, we can capture early temperature changes and gas release phenomena. This provides data support for prediction model.

b. LSTM time-series prediction algorithm

We use LSTM to build a time-series prediction model. It can model the temperature and gas concentration data in dynamic way and it has memory cells and gating mechanisms to learn temporal dependencies. In fact, with these features it can capture the subtle trends of various parameters during thermal runaway. Then the thermal runaway risk in next few minutes can be predicted with good accuracy.

c. Edge computing deployment technology

We quantize the LSTM model and make it lightweight for deployment on ESP32-S3 microcontroller, combined with FreeRTOS for multi-task scheduling. In fact, we use CMSIS-NN library to accelerate the computation and single inference latency can be controlled within 50ms. It can achieve millisecond-level warning response.

(2) The innovations

In traditional BMS, fixed threshold is used for alarm, so it is hard to detect early trend changes of thermal runaway. In fact, the system can only react after accident happens.We use LSTM time-series prediction model. It can change from post-accident alarm to pre-accident prevention, and warning is issued several minutes in advance so users can have valuable response time.

Existing BMS generally lack ability to sense characteristic gases. In fact, these gases are key early indicators of thermal runaway and they can tell us the battery status before the accident happens.We integrate gas concentration sensors in this work so that temperature and gas concentrations can be monitored together and in principle a full early warning system for thermal runaway can be built to improve the safety of the battery system.

Different from cloud-dependent solutions, we deploy LSTM model directly on ESP32-S3 microcontroller at the edge. It can form a localized closed loop where the system handles data acquisition, real-time analysis, warning generation and response together. Network latency can be avoided. In fact, the warning is expected to be real-time and reliable.

Existing safety warning methods often should be integrated into BMS or vehicle systems. It can bring high cost and the modification is difficult. It is worth noting that our design is external and independent, so it requires no modification to original system, and we can use plug-and-play method with low cost, and it should be suitable for mass consumer scenarios such as new energy vehicles, electric bicycles, portable energy storage devices and other similar applications.

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