LI-ion NOSE : A Multi-Parametric Sensor Fusion Framework for Pre-Thermal Runaway Detection

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ABSTRACT

Lithium-ion batteries are the dominant power source for modern electronics, yet they remain vulnerable to "thermal runaway"—a catastrophic failure mode often preceded by electrolyte off-gassing 5–20 minutes before critical temperature spikes occur. Addressing the latency limitations of traditional temperature-only Battery Management Systems (BMS), this paper presents a low-cost, standalone early warning system based on the ESP8266 microcontroller. The proposed prototype utilizes a **Sensor Fusion** algorithm that correlates real-time gas anomalies (using an MQ-135 sensor) with thermal **Rate-of-Rise (RoR)** analysis (using a DS18B20 probe). By implementing a tiered "Safety Ladder" logic, where gas detection triggers a pre-warning and rapid heating triggers a critical alarm, the system significantly reduces false positives while capitalizing on the "Golden Window" of pre-failure detection. Experimental validation using combustion surrogates demonstrates that this multi-modal approach offers a reaction time advantage of several minutes compared to conventional thermal monitoring.

Keywords: *Thermal Runaway, Sensor Fusion, Li-ion Safety, Rate-of-Rise (RoR), Volatile Organic Compounds (VOCs), Embedded Systems.*

I. INTRODUCTION

The proliferation of Lithium-ion (Li-ion) technology underpins the shift toward electric mobility and portable energy storage. However, the electrochemical instability of Li-ion cells under stress (mechanical abuse, overcharging, or internal shorts) poses a severe safety risk. Thermal runaway is a self-propagating exothermic reaction that, once initiated, is often irreversible and leads to fire or explosion.

Crucially, these failure events are rarely instantaneous. Research indicates they are preceded by a "silent" phase of electrolyte decomposition, characterized by the venting of Volatile Organic Compounds (VOCs) such as Ethylene Carbonate (EC) and Hydrogen Fluoride (HF) [1, 2]. Standard BMS solutions often rely on NTC thermistors to detect absolute temperature thresholds (e.g., T > 60°C). However, due to the thermal mass of the battery pack, there is a significant "Thermal Lag" between internal failure and external sensor registration [3, 4].

To bridge this detection gap, this research introduces the **"LI-ION NOSE,"** an offline embedded system designed to function as a digital olfactory unit. By synthesizing early gas evolution data with thermal rate analysis, the system provides preemptive alerts, allowing for intervention before the thermal event becomes catastrophic.

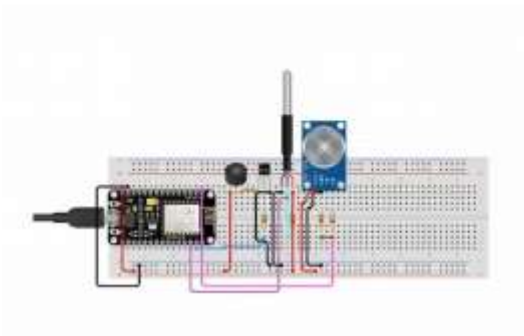
II. METHODS AND MATERIAL

- This section details the hardware architecture, sensing components, and algorithmic methodology employed in the development of the **LI-ION NOSE** early hazard detection prototype.

A. System Architecture

The system is built as a standalone embedded module designed for retrofitting into battery packs or charging stations. The architecture prioritizes low latency and offline reliability.

1. **Microcontroller:** ESP8266 (NodeMCU) running at 80MHz, selected for its low power consumption and 3.3V logic compatibility.
2. **Chemical Sensing (The "Nose"):** An MQ-135 Metal Oxide Semiconductor sensor is employed to detect the "chemical signature" of battery failure. It is highly sensitive to the organic solvents (carbonates) vented during the initial stages of electrolyte breakdown[3].
3. **Thermal Sensing (The "Skin"):** A DS18B20 digital probe provides precise local temperature data via the 1-Wire protocol[5], minimizing signal noise common in analog thermistors.
4. **Alert Interface:** A local audiovisual interface (Active Buzzer + Status LED) ensures immediate user notification without reliance on external network connectivity.



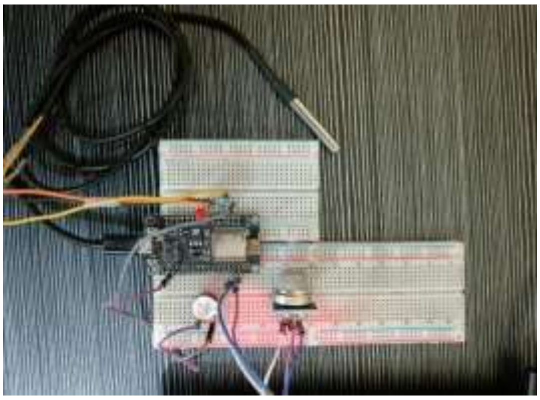


Fig-1,2: *Hardware connections Diagram of the LI-ION NOSE Prototype(simulation vs real).*

B. Sensor Fusion Methodology

The core innovation of this work is the transition from simple threshold-based monitoring to a **Rate-of-Rise (RoR)** logic combined with chemical sensing.

- **Gas Logic:** The system establishes a baseline reading for "clean air" upon initialization (typically raw analog values of 70-80). A deviation of 30% from this baseline is flagged as a "Gas Anomaly."
- **Thermal Logic:** Instead of waiting for a high absolute temperature (e.g., 60°C), the system calculates the derivative of temperature with respect to time (dT/dt).

$$RoR = (T\_current - T\_previous) / \Delta t$$

A rise rate exceeding 1.0°C/secs is treated as a confirmed thermal runaway event, regardless of the absolute starting temperature.

C. The "Safety Ladder" Mechanism

To minimize false alarms (e.g., from ambient solvents or normal usage heat), the system employs a tiered decision tree:

1. State 0 (Normal): Gas nominal, RoR nominal. (LED OFF).
2. State 1 (Pre-Warning): Gas Anomaly Detected (G > Threshold).
   - *Diagnosis:* Potential slow leak or initial venting.
   - *Action:* Intermittent Beep + Blinking LED.
3. State 2 (Critical Alarm): (Gas Anomaly Detected) AND (RoR > 1.0°C/secs).
   - *Diagnosis:* Confirmed active failure mechanism.
   - *Action:* Continuous Siren + Solid LED.

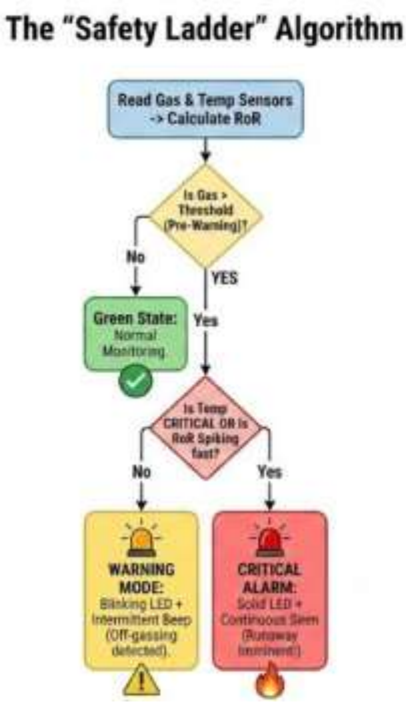


Fig-3: Control flow of safety ladder

III. RESULTS AND DISCUSSION

This section presents the empirical validation of the **LI-ION NOSE** prototype, focusing on its ability to provide early, reliable hazard detection through sensor fusion and its efficacy in reducing false positives compared to conventional monitoring.

A. Experimental Setup and Data Acquisition

The prototype was evaluated in a controlled laboratory environment at an ambient temperature 26°C ± 1°C. The test rig consisted of the sensor module mounted on a breadboard, positioned 5 cm from the stimulus source to replicate the close confines of a battery enclosure.

- **Surrogate Stimuli:**
  - **Chemical Stimulus:** To simulate the release of electrolyte vapors (VOCs) and smoke during cell venting, an incense stick and isopropyl alcohol vapor were introduced to the MQ-135 sensor's intake.
  - **Thermal Stimulus:** To replicate the rapid exothermic heating of a thermal runaway event, a concentrated heat source (controlled flame/lighter) was applied near the DS18B20 probe.
- **Data Acquisition:** Sensor data was logged in real-time via the ESP8266 serial interface at a baud rate of 115200. The sampling interval was set to 500ms to ensure high-resolution capture of the Rate-of-Rise spikes.

B. Results and Discussion

The system was subjected to a multi-stage stress test to validate the "Safety Ladder" logic. The response characteristics observed are detailed below:

1. **Baseline Phase (t=0s to 10s):** During the initialization period, the system demonstrated stability. The MQ-135 registered raw analog values oscillating between 77–80, representing the "clean air" baseline. The DS18B20 maintained a stable reading of 26°C - 27°C with a negligible Rate-of-Rise (0.01 – 0.06°C/sec) No alerts were triggered, confirming the system's resistance to static noise.
2. **Gas Response Phase (t=12s):** Upon the introduction of the chemical surrogate, the system exhibited an immediate reaction. The MQ-135 sensor readings spiked from the baseline of ~80 to **287–298** within 3–4 data iterations (approximately 2 seconds). This sharp gradient triggered **State 1 (Pre-Warning)**. Crucially, the temperature remained stable during this phase. This validates the system's ability to utilize the "Golden Window," detecting the failure precursor potentially minutes before any heat is generated [1, 3].
3. **Thermal Shock Phase (t=22s):** When the thermal stimulus was applied, the DS18B20 registered a rapid climb (27°C - 70°C - 90°C) within seconds. The internal algorithm calculated a Rate-of-Rise significantly exceeding the threshold (>1.0°C/s). The combination of the active Gas Anomaly and the Thermal Spike triggered **State 2 (Critical Alarm)** within 5 seconds of heat application.
4. **False Positive Suppression (Interoperability):** A separate test was conducted where only a heat source was applied slowly (simulating heavy load) without gas presence. The temperature rose to 50°C, but the Rate-of-Rise remained below 0.5°C/s, and gas levels remained at baseline. The system correctly remained in **State 0 (Normal)**, demonstrating that high temperature alone—without the chemical signature of failure or a critical rise rate—does not trigger a false evacuation alarm.

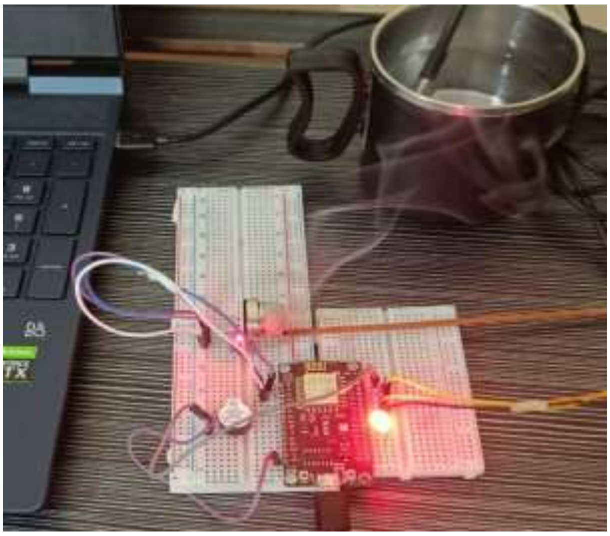


Fig 4: Critical Alert for high temp and gas detection

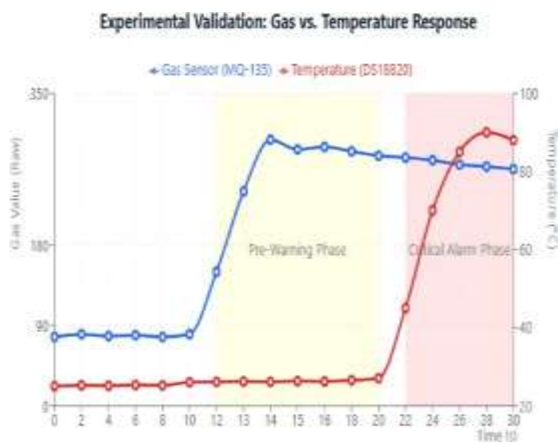


Fig-5: Graph for gas and temp responses(Gas AND Rate > 1.0)

C. Limitations and Future Work

Limitations: Despite the successful validation of the sensor fusion logic, the current prototype presents certain limitations:

- **Sensor Specificity:** The MQ-135 is a general-purpose VOC sensor with high cross-sensitivity to common household vapors (e.g., cleaning agents, alcohol). While the "Safety Ladder" mitigates this via thermal verification, the "Pre-Warning" state remains susceptible to environmental noise.
- **Surrogate Testing:** Due to safety constraints, validation relied on combustion surrogates (incense and external heat sources) rather than destructive battery testing. Precise calibration against specific electrolyte vapor concentrations (ppm) is necessary for industrial deployment.

Future Scope: To address these limitations and transition from prototype to product, future work will focus on:

- **Enhanced Sensing:** Integrating selective electrochemical sensors for Hydrogen Fluoride (HF) detection to pinpoint battery-specific off-gassing signatures.
- **Machine Learning:** Implementing lightweight Edge AI models to classify gas signatures, further reducing false positives by distinguishing between harmless environmental VOCs and electrolyte vapors.
- **Miniaturization:** Developing a custom PCB form factor designed to fit directly inside standard battery pack enclosures, improving thermal coupling and reducing system footprint.

IV. CONCLUSION

This study successfully designed and validated the LI-ION NOSE, a low-cost, offline early hazard detection system. By fusing chemical sensing with thermal rate analysis, the prototype addresses the critical "Thermal Lag" deficiency inherent in traditional Battery Management Systems.

Key Contributions:

- **Latency Reduction:** Experimental results confirm that detecting gaseous precursors offers a significant time advantage. The system successfully identified the "Pre-Warning" state via gas detection well before the thermal event occurred, effectively validating the use of the "Golden Window" for evacuation lead time[4].
- **Robustness via Sensor Fusion:** The standalone ESP8266-based design ensures reliability even in the absence of network connectivity. Furthermore, the "Safety Ladder" logic effectively filters out false positives by requiring multi-parametric verification for critical alarms.

V. REFERENCES

[1] Koch, S., Birke, K. P., & Kuhn, R. "Fast Thermal Runaway Detection for Lithium-Ion Cells in Large Scale Traction Batteries," *Batteries*, vol. 4, no. 2, p. 16, 2018.

[2] Finegan, D. P., et al. "In-operando high-speed tomography of lithium-ion batteries during thermal runaway," *Nature Communications*, vol. 6, p. 6924, 2015.

[3] Essl, C., et al. "Early Detection of Failing Automotive Batteries Using Gas Sensors," *Batteries*, vol. 7, no. 2, p. 25, 2021.

[4] Yuan, L., et al. "Early detection of thermal runaway in lithium-ion batteries based on gas sensing," *Journal of Energy Storage*, 2020.

[5] Maxim Integrated, "DS18B20 Programmable Resolution 1-Wire Digital Thermometer Datasheet," 2019.