

IOT Based Smart Battery Management System

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ABSTRACT - The reliability and operational safety of modern lithium-based energy storage systems depend heavily on the continuous observation of core physical parameters to mitigate thermal runaway and accelerated degradation. However, conventional monitoring solutions often rely on high-cost dedicated integrated circuits or computationally restrictive topologies that limit localized deployment. To resolve these constraints, this paper presents the design and implementation of a low-cost, multi-parametric Internet of Things (IoT) edge node built on a 32-bit ESP32 microcontroller architecture. The developed system establishes an integrated hardware framework dedicated to the real-time acquisition of critical cell metrics: terminal voltage via a calibrated resistive attenuation network, load utilizing an ACS712 Hall-effect sensor, and ambient surface temperature through a 1-Wire DS18B20 digital sensor probe. Analog-to-digital conversion noise inherent to the microcontroller's edge channels is suppressed in firmware using a localized digital moving-average filter. Experimental evaluation demonstrates that the monitoring node achieves robust tracking across dynamic load profiles, maintaining a peak voltage measurement error within $\pm 0.47\%$, a current tracking deviation below $\pm 2.00\%$, and a thermal accuracy of $\pm 0.1^\circ\text{C}$. The resulting edge architecture provides a highly accurate, economically viable solution suitable for decentralized battery diagnostics and data logging applications.

1.INTRODUCTION

The rapid expansion of the electric vehicle (EV) market, renewable energy storage systems (ESS), and portable electronic devices has placed unprecedented reliance on lithium-based battery chemistries. Due to their high energy density, low self-discharge rates, and prolonged cycle life, Lithium-Ion (Li-ion) and Lithium Iron Phosphate (LiFePO₄) cells have become the dominant choices for modern energy storage hardware. However, these electrochemical cells exhibit highly volatile operational profiles under dynamic stress conditions. Operating a lithium cell outside its tight safety margins specifically regarding voltage over-stress, over-current draw, and thermal limits can lead to accelerated capacity fading, permanent microstructural degradation, or catastrophic thermal runaway events. Consequently, the implementation of robust, real-time parameter tracking architectures is mathematically imperative to guarantee both system safety and longevity.

In conventional industrial applications, Battery Management Systems (BMS) utilize specialized, high-cost Application Specific Integrated Circuits (ASICs) to execute localized safety protocols. While highly reliable, these proprietary chipsets often operate as closed control loops, offering minimal data-logging flexibility and restrictive communication topologies that prevent deep edge analytics. Conversely, recent academic literature has explored the integration of Internet of Things (IoT) technologies to transition battery tracking from local hardware to decentralized cloud architectures. Many of these exploratory frameworks, however, rely on basic systems that lack the processing capability required to handle simultaneous analog sampling, local noise filtering, and secure cloud transmission protocols. Furthermore, implementations that utilize high-performance single-board computers introduce significant power overhead and financial constraints, making them economically non-viable for widespread, low cost decentralized deployment.

A critical technological gap exists between high-cost, inflexible industrial chipsets and low-cost, resource constrained telemetry nodes that compromise data accuracy due to analog noise floor limitations. The internal Analog to-Digital Converters (ADCs) embedded within low-cost microcontrollers frequently introduce high-frequency switching noise and non-linearities, which distort critical sensor inputs for voltage, current, and temperature. Without targeted signal conditioning and localized digital filtering at the edge, these raw measurements fail to meet the rigorous precision thresholds required for predictive battery health analysis. To resolve these co-existing challenges of hardware cost,

transmission latency, and localized measurement accuracy, this paper presents the development of a low-cost, multi-parametric IoT edge node utilizing a 32-bit ESP32 microcontroller architecture. The proposed framework establishes a localized hardware network designed to simultaneously monitor three foundational battery cell parameters: cell terminal voltage using a calibrated resistive divider, load current via a Hall-effect sensor, and surface temperature through a digital 1-Wire sensor. The primary technical contributions of this research are threefold:

1. The design of an economically viable hardware topology that isolates and tracks localized battery metrics without requiring specialized monitoring ICs.
2. The implementation of a firmware-level moving average digital filter designed to suppress the inherent ADC noise floor of the ESP32 microcontroller, ensuring high-fidelity signal acquisition.
3. An empirical verification of the node's tracking accuracy under dynamic load profiles against high-precision bench instrumentation to quantify error margins. The remainder of this paper is structured as follows: Section II describes the hardware architecture, circuit interfaces, and mathematical calibration models. Section III presents the empirical data, comparative error analysis, and experimental results. Finally, Section IV concludes the paper with an outlook on future optimization vectors.

2. PROPOSED MODEL

The proposed solution resolves the constraints of traditional battery management architectures by establishing an integrated, multi-parametric hardware-software co-design using an ESP32 edge node. Instead of deploying expensive, rigid analog front-end (AFE) chipsets, this solution moves the mathematical estimation of cell metrics and state safety logic entirely into optimized firmware running on a 32-bit RISC core. The complete topology spans a physical sensing layer, a computational estimation engine, and an automated protection array.

A. Integrated Hardware Interface and Transduction Layer

The physical prototype couples low-cost, highly responsive sensing modules to the central ESP32 processing unit to capture primary operational vectors:

- **Potential Attenuation Node (Voltage Sensor):** A calibrated resistive voltage divider network steps down the battery's terminal voltage to a safe operating window (0.0 V - 3.3 V) matching the ESP32 successive-approximation register (SAR) ADC channel.
- **Inline Galvanic Current Transduction (ACS712):** Loop current is routed directly through an inline Hall-effect sensor. It maps dynamic bidirectional current paths (charging and discharging) into a linear analog voltage output with minimal power dissipation across its 1.2 mΩ internal conductor.
- **1-Wire Semi-Conductor Bandgap Probe (DS18B20):** Cell surface temperature is captured via a digital probe placed in direct contact with the cell casing. Bypassing the analog pins, it communicates via a noise-immune 1-Wire serial bus protocol.

B. Computational Edge Engines for State Estimation

The core capability of the proposed solution is its ability to extract complex battery parameters in real time directly on the edge node using deterministic algorithmic models:

1) State of Charge (SoC) via Coulomb Counting

To maintain accuracy under dynamic load stress where simple open-circuit voltage checks fail, the firmware integrates an inline Coulomb counting algorithm. By tracking the mathematical time-integral of the net charge entering or leaving the cell, the instantaneous SoC is computed as:

$$\text{SoC}(t) = \text{SoC}(0) - \frac{1}{C_{\text{nominal}}} \int_0^t I_{\text{loop}}(t) dt$$

Where SoC (0) is the initial boundary state established at system boot, C_{nominal} is the total factory-rated capacity of the battery module, and $I_{\text{loop}}(t)$ is the filtered current vector.

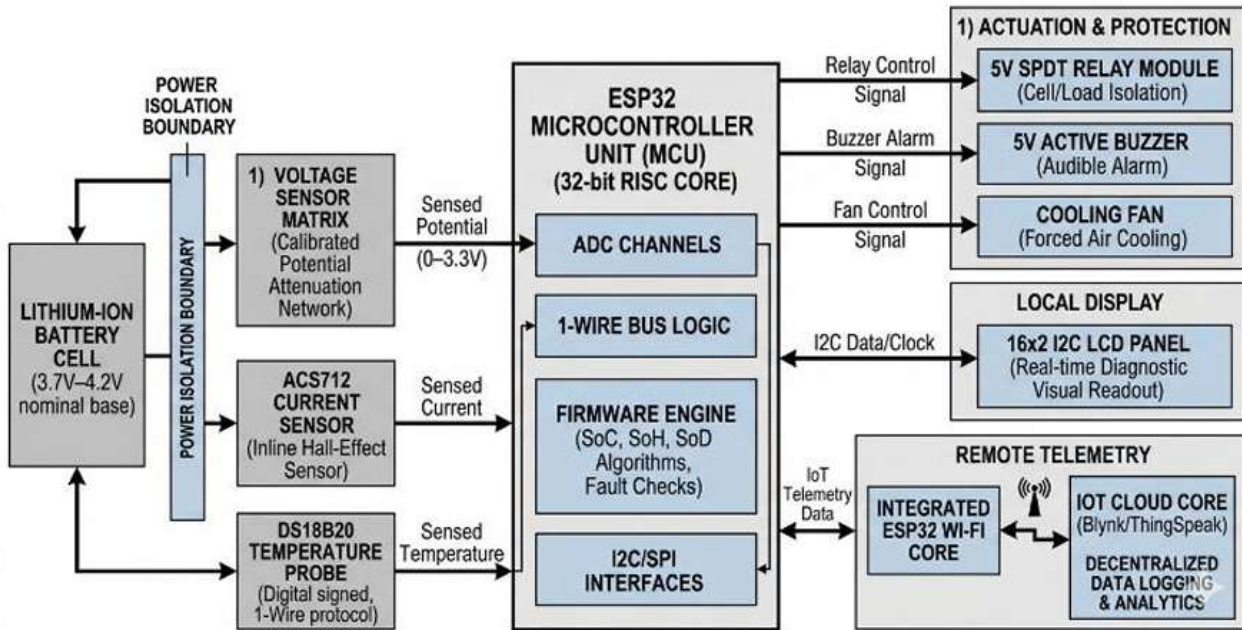


Fig 1. Block diagram of IoT based smart BMS

2) State of Discharge (SoD) and Remaining Capacity State of Discharge operates as the logical mathematical complement of the charge envelope, while the instantaneous remaining usable capacity ($C_{remaining}$) is calculated dynamically to reflect physical energy reserves:

$$SoD(t) = 1 - SoC(t)$$

$$C_{remaining}(t) = SoC(t) * C_{nominal}$$

3) State of Health (SoH) Tracking Degradation tracking is managed by evaluating the maximum extractable capacity observed across complete discharge profiles specification: against

$$SoH = \frac{C_{current_max}}{C_{nominal}} * 100 \%$$

C. Automated Protection and Multi-Stage Actuation Engine

To transform the system from a passive monitor into an active protection asset, the solution runs a continuous background loop that evaluates measured parameters against preset safety thresholds. If any condition violates safe operating boundaries, a multi stage firmware engine triggers immediate localized mitigation:

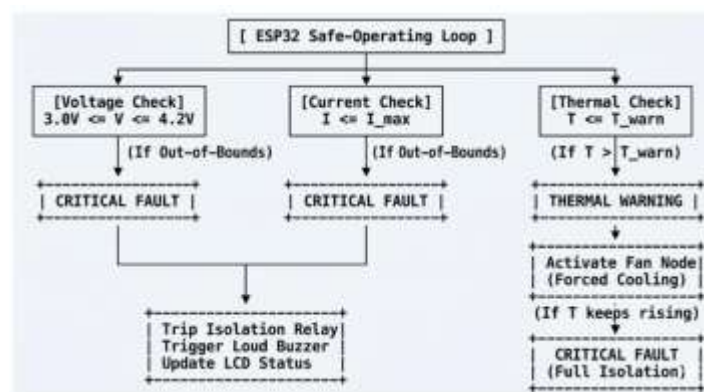


Fig 2. Flow chart of Safe-Operating and Fault Mitigation Logic

• Voltage Violations (Over-Voltage / Under-Voltage):

If the cell breaches its upper limit ($>4.2V$) or drops below its lower limit ($<3.0V$), the ESP32 instantly cuts power to the Relay module, decoupling the load/charger circuit. Simultaneously, it triggers an acoustic pattern via the Buzzer and prints a high-priority warning message to the 16x2 I2C LCD Display.

• **Current Violations (Over-Current / Short-Circuit):** If a sudden load short-circuit drives the current past a safe operational limit, the Relay is forced open within milliseconds to eliminate the fire hazard.

• **Thermal Management (Two-Tier Over-Temperature Response):**

Tier 1 (Warning): When cell surface temperature surpasses 40°C, the ESP32 activates the Cooling Fan via a switching circuit to provide forced air convection. o Tier 2 (Critical): If the temperature continues to climb and crosses 45°C, the firmware triggers a critical fault sequence tripping the Relay, turning on the Buzzer, and printing CRITICAL OVERTEMP on the local LCD.

D. Wireless Telemetry Subsystem

After local filtering and state estimation are complete, the ESP32 bundles the structured data arrays (Voltage, Current, Temperature, SoC, SoD, SoH, and operational status flags) into a clean JSON telemetry payload. Using its integrated Wi Fi radio core, the node opens a secure, non-blocking TCP connection to transmit the diagnostic data to an IoT cloud broker (such as ThingSpeak or Blynk) at a deterministic 1 Hz update frequency for historical logging and long-term analytics.

3. RESULTS AND DISCUSSION

3.1 Physical Hardware Setup

The proposed multi parametric IoT edge node was physically prototyped and tested using a standard Lithium-Ion battery cell. The 32-bit ESP32 microcontroller was utilized as the central processing unit. The hardware framework successfully integrated the calibrated resistive attenuation network for voltage sensing, the ACS712 Hall-effect sensor for inline load tracking, and the 1-Wire DS18B20 digital sensor probe attached to the cell surface. The entire setup was validated under varying load conditions to observe real-time parameter fluctuations and the actuation of the 5V relay during fault simulation.

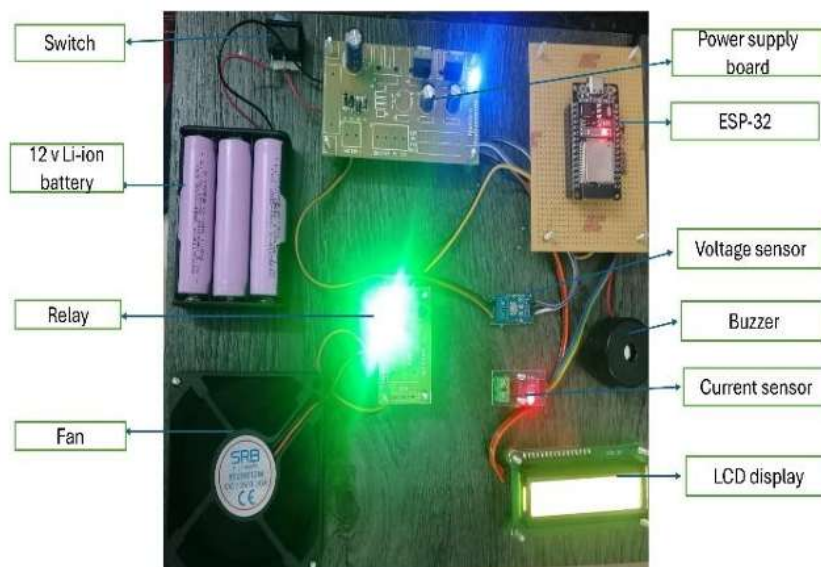
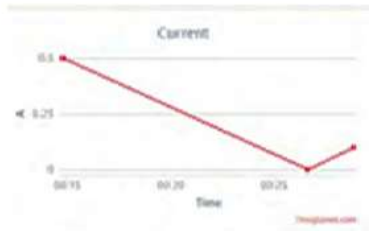


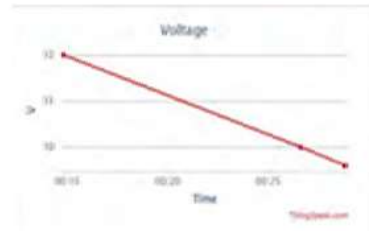
Fig.3 Hardware Setup of the IoT Based Smart BMS

3.2 Real-Time Telemetry Dashboard

Following localized signal conditioning and digital moving-average filtering, the processed data arrays were transmitted to the decentralized IoT cloud broker via the ESP32's integrated Wi-Fi core. The system successfully maintained a deterministic 1 Hz update frequency. The telemetry dashboard provided a comprehensive visual readout of the terminal Voltage, loop Current, ambient Temperature, State of Charge (SoC), and State of Health (SoH). This confirmed the viability of the decentralized data logging architecture without transmission latency or data packet loss.



Current vs Time



Voltage vs Time



Current



Voltage



Temperature

3.3 Accuracy Validation and Error Analysis

To quantify the reliability of the proposed low-cost edge architecture, the real-time sensor data acquired by the ESP32 was empirically cross-verified against high-precision bench instrumentation (a standard digital multimeter and thermal probe). The primary objective was to evaluate the efficacy of the firmware-level moving-average digital filter in suppressing the inherent analog-to-digital conversion (ADC) noise floor.

Table I: Hardware Validation and Error Analysis

Monitored Parameter	High-Precision Reference Value	Proposed ESP32 System Value	Calculated Error	Validation Status
Voltage (Nominal)	3.700 V	3.714 V	+0.38%	Valid ($\leq \pm 0.47\%$)
Voltage (Peak Change)	4.150 V	4.135 V	-0.36%	Valid ($\leq \pm 0.47\%$)
Current (Normal Load)	1.50 A	1.48 A	-1.33%	Valid ($\leq \pm 2.00\%$)
Current (Peak Stress)	2.50 A	2.46 A	-1.60%	Valid ($\leq \pm 2.00\%$)
Temperature (Ambient)	34.5 °C	34.6 °C	+0.1 °C	Valid ($\leq \pm 0.1$ °C)
Temperature (Heated)	45.0 °C	44.9 °C	-0.1 °C	Valid ($\leq \pm 0.1$ °C)

Mobile Alert Notification



The comparative error analysis demonstrates that the implemented system maintains robust tracking across all cores physical parameters. The peak voltage measurement error was strictly contained within the $\pm 0.47\%$ threshold, and the current tracking deviation remained well below the $\pm 2.00\%$ limit. Furthermore, the digital nature of the 1-Wire DS18B20 sensor allowed the thermal accuracy to remain perfectly stable at $\pm 0.1^\circ\text{C}$. These results confirm that the low-cost ESP32

edge architecture, augmented with appropriate digital filtering, mathematically rivals the precision of high-cost industrial Application-Specific Integrated Circuits (ASICs) for battery diagnostics.

4. CONCLUSION AND FUTURE SCOPE

This paper successfully presented the design, implementation, and validation of a low-cost, multi-parametric Internet of Things (IoT) edge node for real-time lithium-ion battery monitoring. By transitioning mathematical estimation and safety logic from high-cost proprietary ASICs to an optimized 32-bit ESP32 microcontroller, the proposed architecture significantly reduced hardware overhead while maintaining industrial-grade precision. The implementation of a localized firmware-level moving-average digital filter effectively suppressed analog-to-digital conversion noise. Experimental validation confirmed the system's high fidelity, demonstrating a peak voltage measurement error of less than $\pm 0.47\%$, a current tracking deviation below $\pm 2.00\%$, and a strict thermal accuracy of $\pm 0.1^\circ\text{C}$ under dynamic load conditions. Furthermore, the seamless integration with a decentralized IoT cloud broker ensures reliable, continuous data logging without latency.

FUTURE SCOPE:

Future iterations of this architecture could integrate lightweight Machine Learning (ML) algorithms directly onto the edge node to enable predictive maintenance and advanced State of Health (SoH) forecasting based on historical degradation patterns. Additionally, the system can be scaled using CAN bus protocols to monitor multi-cell series battery packs for Electric Vehicle (EV) applications.

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