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IoT-Enabled Battery Health Monitoring and Data Logging System for Electric Vehicles

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ABSTRACT :

The reliable operation of an electric vehicle (EV) depends on the electrical and thermal condition of its battery pack. Voltage, current and temperature vary with load, charge–discharge cycling and ageing; therefore, continuous monitoring and dependable data retention are important for assessing battery operation. This paper presents an IoT-enabled battery monitoring and black-box data logging prototype based on an ESP32 microcontroller. The proposed arrangement combines an INA219 voltage/current sensor, a DS18B20 temperature sensor, a DS3231 real-time clock (RTC), a microSD storage module and Wi-Fi connectivity. The ESP32 acquires and validates sensor readings, applies configurable threshold checks, updates local indicators and stores timestamped measurements and fault events on the microSD card. When a network connection is available, selected data can be transmitted to a cloud dashboard for remote monitoring and trend visualisation. State of charge (SOC) and state of health (SOH) are considered derived indicators rather than direct sensor outputs; their accuracy depends on the estimation method, calibration and validation procedure. The paper details the system architecture, methodology, component roles, data flow and proposed validation plan. Since a complete experimental dataset and measured performance results were not supplied, no quantitative accuracy or reliability claims are made. The design is presented as a prototype monitoring aid and not as a replacement for an independently protected, vehicle-grade battery management system.

Keywords—Electric vehicles, battery monitoring, Internet of Things, ESP32, data logging, black-box system, state of charge, state of health, lithium-ion battery.

I. INTRODUCTION

Electric vehicles are increasingly adopted as an alternative to conventional vehicles, and their performance depends substantially on the condition of the energy-storage system. Lithium-ion battery packs are widely used because of their high energy density and power capability. However, battery characteristics change during operation and throughout their service life. Repeated cycling, elevated temperature, high current demand, deep discharge and cell-to-cell variation can contribute to capacity degradation and increased internal resistance [4], [7], [8].

A battery management system (BMS) supervises battery operation and performs functions such as voltage and temperature measurement, current monitoring, protection, cell balancing and estimation of battery condition. A monitoring prototype can complement these functions by making selected measurements visible to users and by retaining operating history. Pack-level measurements are useful for observing overall behaviour, but they cannot reveal every cell-level imbalance or internal fault. Independent battery protection must therefore remain in place.

Internet of Things (IoT) connectivity enables measurements to be viewed remotely through a web or mobile dashboard. Nevertheless, cloud-only monitoring is vulnerable to network interruptions. A local black-box recorder addresses this limitation by retaining timestamped readings and fault events on removable storage, even when Wi-Fi is unavailable. The proposed system combines local acquisition, embedded processing, local alerts, microSD logging and optional cloud communication in a single prototype.

A. Aim and Objectives

The aim is to develop a compact prototype for monitoring selected battery parameters and preserving their operating history. The objectives are to: (1) measure battery voltage, current and surface temperature; (2) acquire and process sensor data using an ESP32; (3) attach date-and-time information to each record; (4) provide local status and warning indications; (5) store measurements and fault events on a microSD card; (6) transmit selected data to a cloud dashboard when Wi-Fi is available; and (7) provide a framework for SOC and SOH estimation subject to calibration and validation.

II. SYSTEM ARCHITECTURE

The system is organised into sensing, edge-processing, local-response and data-management functions. The sensing function measures electrical and thermal parameters. The ESP32 performs acquisition, validation, threshold evaluation and communication control. Local outputs provide immediate status information, while the microSD card and cloud dashboard provide local and remote data access, respectively.

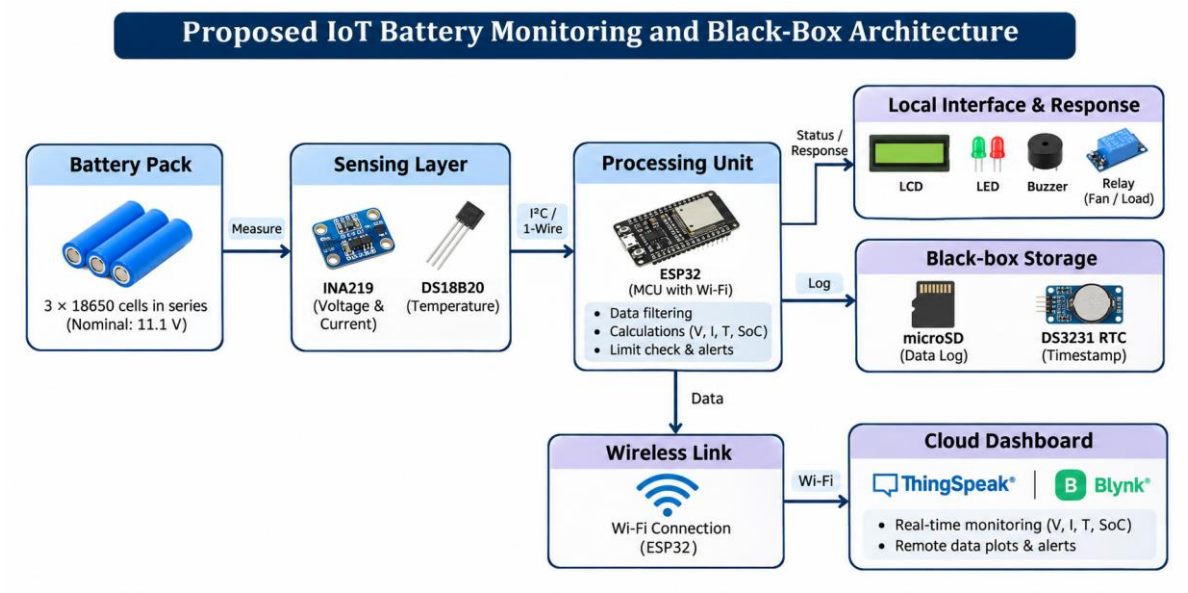


Fig. 1. Physical prototype of the IoT-based battery monitoring and data logging system.

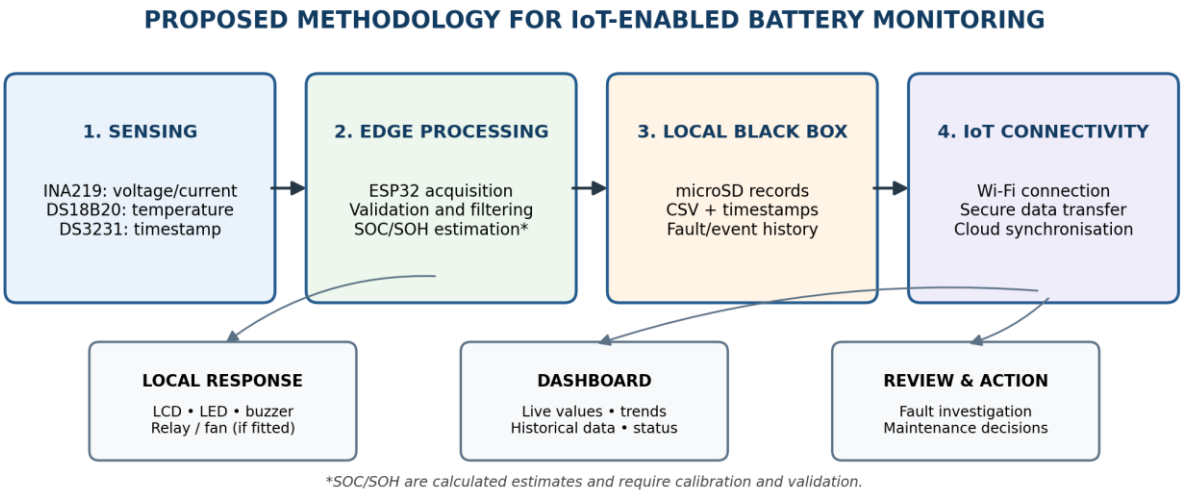


Fig. 2. Proposed system methodology and information flow.

A. Battery Pack and Power Arrangement

The prototype description identifies three 18650 lithium-ion cells connected in series. For cells with a nominal voltage of approximately 3.7 V each, the nominal pack voltage is approximately 11.1 V, while the fully charged voltage may reach approximately 12.6 V; the actual limits must follow the selected cell manufacturer's specification. The pack must be connected through a correctly rated three-series-cell BMS that provides the required cell-level overcharge, over-discharge and overcurrent protection, with balancing where supported. A regulated DC–DC converter supplies the control electronics. Its input range, output voltage, current capacity, thermal rating and grounding arrangement must be verified before operation.

The prototype is not a certified traction-battery BMS. The independent BMS, fuse, suitable wiring, insulation and enclosure remain essential. Software, Wi-Fi or relay failure must not disable the battery's independent protection.

B. Hardware Components

Component	Function	Interface / Design Consideration
ESP32 microcontroller	Reads sensors, processes measurements and manages outputs and Wi-Fi.	Check GPIO allocation, logic levels, supply stability and peripheral compatibility.
INA219 sensor	Measures bus voltage and current through its shunt measurement path.	I²C; verify bus-voltage rating, shunt rating and current range for the actual pack/load.
DS18B20 sensor	Measures battery-surface temperature.	1-Wire; use the required pull-up resistor and secure, repeatable thermal contact.
DS3231 RTC	Provides date and time for measurement and event records.	I²C; set and verify time before data collection.
microSD module	Stores timestamped measurements and fault/event records locally.	Check supply and logic-level compatibility; handle card errors and write failures.
LCD, LED and buzzer	Provide local measurement display and	Define clear normal, warning and critical states.

	visual/audible warnings.	
Relay and DC fan	Provide a demonstrator cooling response when configured temperature limits are reached.	Verify DC contact rating, fan current, transient protection and fail-safe behaviour.
Wi-Fi / cloud dashboard	Makes selected measurements and trends available remotely.	Document platform, protocol, upload interval and credential protection.

III. PROPOSED METHODOLOGY

A. Data Acquisition and Sensing

The INA219 is connected to the ESP32 through the I²C interface to obtain bus-voltage and current measurements. The DS18B20 is mounted at a defined location on the battery surface and communicates through a 1-Wire interface. The DS3231 RTC supplies date-and-time information. Each measurement is converted into engineering units and checked for validity before it is used by subsequent processing stages. The firmware sampling interval and sensor mounting locations should be fixed and documented during testing. Surface temperature is an indication of local external temperature and may differ from the internal cell temperature.

B. Edge Processing and Data Validation

The ESP32 reads the sensor values, checks for missing or out-of-range readings and applies the selected filtering method to reduce short-duration noise. Valid measurements are associated with an RTC timestamp. The firmware then evaluates configured voltage, current and temperature limits and prepares the data for display, storage and transmission. Invalid sensor data must be marked as invalid and must not be interpreted as a normal battery condition.

C. SOC and SOH Estimation

SOC represents the estimated remaining charge relative to the usable battery capacity under defined conditions. Possible approaches include a calibrated open-circuit-voltage relationship, coulomb counting or a combination of both. Voltage-based estimation requires a cell-chemistry-specific voltage–SOC relationship and is affected by load and relaxation history. Coulomb counting integrates measured current over time and requires a known initial SOC, accurate current measurement and compensation for capacity and efficiency effects.

SOH represents the present battery condition relative to a reference condition. It may be estimated from measured usable capacity or from a calibrated internal-resistance indicator. A capacity-based expression is SOH (%) = (measured usable capacity / reference capacity) × 100. Resistance-based estimates require controlled test conditions because temperature and operating state also influence resistance. Accordingly, SOC and SOH values must be labelled as estimates until their methods and accuracy have been validated.

D. Threshold-Based Decision Logic and Alerts

The firmware compares valid measurements with configurable operating limits. A voltage value outside its permitted range, excessive current, elevated temperature or a sensor fault can trigger an event record and a warning indication. The LCD presents the operating state, while LEDs and a buzzer provide immediate local alerts. A relay-controlled fan may be used as a demonstrator response to elevated measured temperature. Any switching device must be rated for the actual DC voltage and fault current; the fan is not a substitute for engineered battery thermal management.

Monitored condition	Possible interpretation	Proposed response
Voltage outside configured range	Possible overcharge, deep discharge, wiring issue or measurement fault.	Record event, show fault and alert the user; independent BMS protection remains essential.
Current above configured limit	Potential overload or abnormal load demand.	Record event and issue warning; disconnect only through a safely engineered, correctly rated device.
Temperature above configured limit	Thermal condition requiring attention.	Record event, activate warning and operate the fan only if the thermal design supports it.
Sensor reading missing or invalid	Open circuit, communication issue or sensor malfunction.	Mark data invalid and raise a sensor fault; do not treat missing data as normal.
SOH below service criterion	Possible capacity fade or increased resistance.	Flag for controlled battery assessment; do not infer a cell-level failure from pack data alone.

E. Black-Box Data Logging

The microSD card provides local storage independent of Wi-Fi availability. Each record should contain the RTC timestamp, voltage, current, temperature, estimated SOC/SOH when implemented, system status and active fault code. A consistent format such as comma-separated values (CSV) supports later inspection and analysis. The firmware should check card availability, handle file creation and write errors, periodically flush data and indicate storage faults. Power-loss behaviour should be assessed to minimise incomplete or corrupted records.

F. IoT Communication and Dashboard

When a configured Wi-Fi network is available, the ESP32 transmits selected measurements to a cloud service such as ThingSpeak or Blynk. The dashboard can display live values, historical trends and alert states. The local microSD logger must continue operating when the network is unavailable. The final implementation should identify the selected cloud platform, communication protocol (for example, HTTP or MQTT), upload interval, data fields and reconnection behaviour. Network credentials should be protected and excluded from publicly shared source code.

G. Black-Box Review and Fault Investigation

After an abnormal event, stored records can be retrieved from the microSD card and reviewed alongside the timestamped measurements. The

sequence of voltage, current and temperature values before and after an event may help identify operating patterns and support maintenance decisions. This review is intended to assist investigation; it does not guarantee identification of the root cause or detection of every internal battery fault.

IV. IMPLEMENTATION AND VALIDATION PLAN

The prototype should be evaluated using controlled tests before any broader deployment. Measurements must be compared with suitable reference instruments, and all test conditions, calibration settings, firmware versions and sampling intervals should be documented. Battery tests must remain within manufacturer limits and be conducted with appropriate independent protection.

Test case	Procedure	Evidence to record
Normal operation	Operate the pack under a safe representative load within manufacturer limits.	Reference and measured voltage/current/temperature; display state; stored records.
Voltage warning	Use a controlled test setup or simulated input to cross the configured threshold.	Threshold, warning latency, event record and dashboard state.
Overcurrent warning	Apply a controlled load within safe test limits or inject a test value in firmware.	Current response, alert behaviour and switching response if fitted.
Temperature warning	Use a controlled temperature source or simulated input; do not heat cells unsafely.	Temperature reading, alert activation and fan response.
Wi-Fi interruption	Disconnect network access while local measurements continue.	Confirmation that local logging continues and records remain readable.
Storage fault	Test missing, full or unavailable microSD conditions without risking the battery.	Storage error indication and firmware behaviour.
SOC/SOH validation	Compare estimates with a defined reference test under controlled conditions.	Estimation error, test conditions and repeatability.

A. Performance Measures

Relevant evaluation measures include voltage and current measurement error, temperature error, sampling interval, alert latency, successful log-write rate, data availability during network outages, Wi-Fi upload success rate and SOC/SOH estimation error. These metrics should be calculated from repeated experiments. Numerical results should be reported only after the corresponding tests have been completed.

B. Safety and Deployment Considerations

The proposed arrangement is a prototype monitoring system, not an automotive-grade BMS. A single surface-temperature sensor cannot establish the temperature of every cell, and pack-level voltage/current measurements cannot identify all cell imbalance or internal faults. The INA219 module's electrical limits must be checked before connection. The battery requires a correctly rated BMS, fuse, insulated enclosure, suitable wiring and controlled test procedures. Electrical, thermal and mechanical protection must be validated independently before any real-world deployment.

V. DISCUSSION

The main contribution of the proposed architecture is the integration of sensor-based monitoring, local event retention and optional remote supervision in a compact embedded platform. The ESP32 coordinates measurement acquisition, decision logic, local indication and Wi-Fi communication. The microSD recorder complements cloud monitoring by retaining timestamped information during network interruptions. These records can support later analysis of operating trends and abnormal events.

The system's practical performance depends on component ratings, sensor placement, calibration, firmware reliability and the quality of the estimation algorithms. In particular, SOC estimation requires a defined method and initial conditions, while SOH estimation requires capacity- or resistance-related reference measurements. Surface temperature is not equivalent to internal cell temperature. Furthermore, relay and fan control must be engineered for the actual load and must not interfere with independent battery protection. These limitations make controlled validation an essential next step.

VI. CONCLUSION AND FUTURE WORK

This paper has presented an IoT-enabled battery monitoring and black-box data logging prototype for electric-vehicle battery applications. The architecture combines voltage, current and surface-temperature sensing with ESP32-based processing, RTC timestamping, local alerts, microSD storage and optional cloud visualisation. The local recorder is intended to preserve operating measurements and fault events when wireless connectivity is interrupted. SOC and SOH are included as estimation objectives that require battery-specific calibration and experimental validation.

Future work will finalise the sampling interval and battery-specific thresholds; verify the electrical ratings and wiring of each module; implement and validate the selected SOC/SOH algorithms; improve sensor, storage and network error handling; and evaluate the prototype against reference instruments under controlled charge–discharge profiles. Further improvements may include cell-level voltage monitoring, multiple temperature sensors, enhanced thermal management, secure communication and testing under representative EV operating conditions. Until such verification is completed, the system should be regarded as a prototype monitoring aid rather than a certified battery protection system.

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