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IoT Based Smart Battery Management System with Mobile App Monitoring

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A B S T R A C T

This article describes an Internet-of-Things (IoT) based smart battery management system (BMS) for a 12 V lithium-ion pack, built around an ESP32-C6 microcontroller and monitored through a mobile application. The hardware consists of a voltage sensor module, a DS18B20 digital temperature sensor, an INA219 current sensor, a 0.96" I²C OLED display, an LM2596 buck converter for the 5 V supply, and a MOSFET-switched 12 V cooling fan. The firmware measures pack voltage, current and temperature every 2 s, estimates state of charge (SOC) from the pack voltage with first-order smoothing, computes a capacity-based state of health (SOH), estimates the remaining range and charging time, and controls the fan with hysteresis between 32 °C and 35 °C. The ESP32 creates its own Wi-Fi access point and serves the measurements as a JSON message, which the mobile application displays as live metrics. In the recorded operating snapshot the pack voltage was 10.76 V, the current 0.10 A, the power 1.09 W, the temperature 37.6 °C, the SOC 56 %, the SOH 92 % and the estimated range 33 km. These values are a single snapshot and not a full test campaign; the SOC is a voltage-based estimate and the SOH is a capacity-based reference value.

Keywords: battery management system, IoT, ESP32-C6, state of charge, state of health, lithium-ion battery, mobile app monitoring, electric vehicle.

1. Introduction

Electric vehicles (EVs) depend on lithium-ion battery packs, which deliver high energy density but must be operated inside strict voltage, current and temperature limits. A battery management system is the electronic unit that watches these quantities, estimates the internal states of the pack that cannot be measured directly, and protects the cells against over-voltage, deep discharge and overheating [1], [2]. Without such supervision, an overheated or over-discharged pack ages quickly and can become unsafe.

A useful BMS reports more than raw readings. The driver or operator needs the SOC, which acts as the fuel gauge, the SOH, which indicates how much usable capacity remains compared with a new pack, and an estimate of how far the vehicle can still travel [3], [4]. Making this information available on a phone, without a wired connection, removes the need for a dedicated instrument panel and allows the pack to be monitored during testing and demonstration.

In this work a low-cost BMS prototype is built around the ESP32-C6 microcontroller, which provides Wi-Fi connectivity on the same chip. The prototype measures voltage, current and temperature of a 12 V, 2600 mAh lithium-ion pack, computes SOC, SOH, range and charging time, drives a cooling fan, and publishes the data to a mobile application. The contributions are:

- the hardware design of the BMS, with the complete circuit diagram and pin allocation;
- the firmware logic for SOC and SOH estimation, range and charging-time estimation, and temperature-based fan control; and
- the Wi-Fi/JSON interface and a mobile application that shows the live battery metrics, together with an operating snapshot of the prototype.

Section 2 reviews earlier work, Section 3 explains the hardware and firmware, Section 4 presents and discusses the observed results, and Section 5 closes the paper.

2. Literature Review

Xing et al. [1] reviewed battery management systems for electric and hybrid vehicles, covering the measurement, estimation, protection and cell-balancing functions of a BMS. Lu et al. [2] discussed the key issues in lithium-ion battery management for EVs, including SOC and SOH estimation, thermal behaviour and safety. Rahimi-Eichi et al. [7] described the role of the BMS in smart-grid and EV applications and the communication links between the BMS and the rest of the system.

Ranjith Kumar et al. [3] gave a broad review of EV batteries, including battery modelling, thermal management, SOC/SOH estimation and charge–discharge behaviour, and stressed that estimation quality depends on reliable measurements. For SOC, Hannan et al. [4] compared the available estimation approaches and their challenges. Open-circuit-voltage lookup is simple but is accurate only at rest, coulomb counting follows the charge flow but drifts without correction, and model-based filters such as the extended Kalman filter of Plett [5] give higher accuracy at the cost of computation and parameter identification. Cheng et al. [6] developed a BMS with SOC estimation for electrical vehicles and showed how SOC is the basis of the charge and discharge decisions of the system.

The voltage-versus-SOC behaviour of a lithium-ion cell is the basis of the generic battery model of Tremblay et al. [8], in which the terminal voltage follows the SOC and the current. In the present prototype this relationship is used in its simplest form, a linear mapping between the empty and full pack voltages, which is suitable for a low-cost demonstrator.

Taken together, these studies show that a BMS combines sensing, estimation, protection and communication. The present work implements a compact version of this chain on a single Wi-Fi-enabled microcontroller and adds a mobile-app interface to it.

3. System Description and Methodology

The BMS is built around the Waveshare ESP32-C6-DEV-KIT-NX board (ESP32-C6-WROOM-1 module) [10]. Figure 1 shows the complete circuit diagram, in which the battery pack supplies the sensors, the buck converter and the fan, and the microcontroller reads the sensors and drives the fan MOSFET.

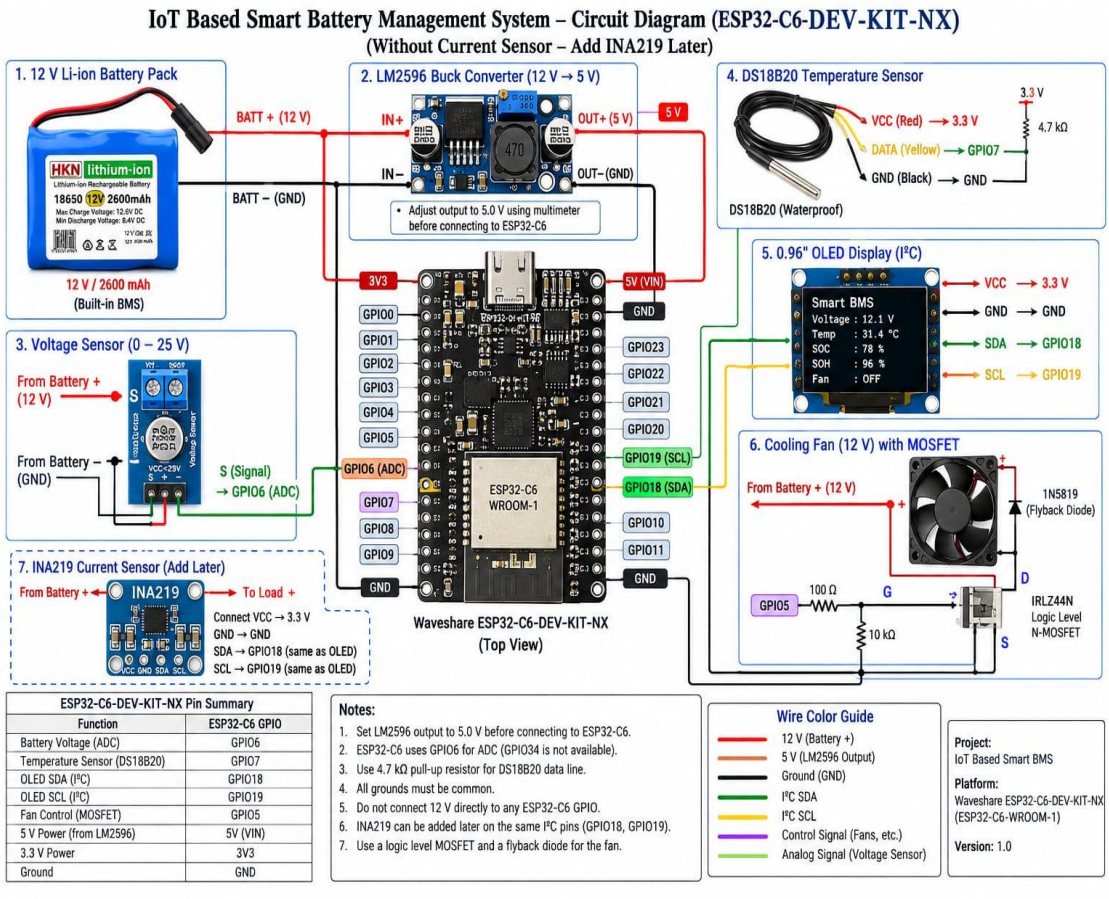


Figure 1. Circuit diagram of the IoT based smart battery management system (ESP32-C6-DEV-KIT-NX).

3.1. System Architecture

A 12 V lithium-ion pack (18650 cells, 12.6 V maximum charge voltage, 8.4 V minimum discharge voltage, built-in protection board) is the energy source. The 12 V rail feeds the LM2596 buck converter, which is adjusted to 5.0 V with a multimeter before it is connected to the 5 V (VIN) pin of the board. The board's 3.3 V output powers the temperature sensor, the OLED display and the current sensor. The battery voltage is measured through a 0–25 V voltage sensor module whose signal pin goes to the ADC input GPIO6. The DS18B20 data line goes to GPIO7 with a 4.7 kΩ pull-up resistor, and the OLED and the INA219 share the I²C bus on GPIO18 (SDA) and GPIO19 (SCL). The 12 V cooling fan is switched by an IRLZ44N logic-level N-MOSFET driven from GPIO5, with a 1N5819 flyback diode across the fan. Table 1 lists the role of each block and Table 2 the pin allocation.

Table 1. Function of the principal blocks of the BMS.

Block	Function
12 V Li-ion pack (2600 mAh)	Energy source with a built-in protection board; 12.6 V full, 8.4 V empty.
LM2596 buck converter	Steps 12 V down to 5.0 V for the ESP32-C6 board.
ESP32-C6-DEV-KIT-NX	Reads the sensors, runs the estimators and fan control, hosts the Wi-Fi access point and web server.
Voltage sensor (0–25 V)	Divider module that scales the pack voltage to the ADC range.
DS18B20	Digital waterproof temperature sensor on a 1-wire bus.
INA219	I²C current and power monitor (added at a later stage).
0.96" OLED	Local display of voltage, temperature, SOC, SOH and fan status.
IRLZ44N + 1N5819	Logic-level MOSFET switch and flyback diode for the 12 V cooling fan.
Mobile application	Shows the live metrics received over Wi-Fi.

Table 2. Pin allocation of the ESP32-C6-DEV-KIT-NX.

Function	GPIO
Battery voltage (ADC)	GPIO6
Temperature sensor (DS18B20)	GPIO7
OLED / INA219 SDA (I²C)	GPIO18
OLED / INA219 SCL (I²C)	GPIO19
Fan control (MOSFET gate)	GPIO5
5 V power (from LM2596)	5V (VIN)
3.3 V power	3V3
Ground	GND (common)

3.2. Sensing

The pack voltage is measured by averaging 40 ADC samples (2 ms apart) at 12-bit resolution, converting the average to a voltage with the 3.3 V reference, and multiplying by the sensor ratio of 5:

$$V_{batt} = (ADC_{avg} \times 3.3 / 4095) \times 5 \quad (1)$$

The current is read from the INA219 over I²C, and the power is computed as $P = V_{batt} \times I$. A positive current denotes discharge and a negative current denotes charging. The temperature is read from the DS18B20; a reading outside −55 °C to 125 °C, or a disconnected sensor, is treated as a sensor error and the fan is kept off. All quantities are refreshed every 2 s.

3.3. State of Charge Estimation

The voltage-based SOC is obtained by linear interpolation between the empty and full pack voltages of 8.4 V and 12.6 V:

$$SOC_V = [(V_{batt} - 8.4) / (12.6 - 8.4)] \times 100 \quad (2)$$

and is limited to the range 0–100 %. To avoid abrupt jumps caused by load-dependent voltage changes and ADC noise, the reported SOC is passed through a first-order smoothing filter with a factor of 0.25:

$$SOC(k) = SOC(k-1) + 0.25 \times [SOC_V(k) - SOC(k-1)] \quad (3)$$

The estimate is stored in the non-volatile memory of the ESP32 once per minute. The firmware also contains a coulomb-counting routine, $SOC = SOC - (I \times \Delta t / Q_n) \times 100$, with Q_n the reference capacity in Ah, but in the present version the reported SOC follows the voltage-based estimate. The remaining capacity and the consumed capacity follow from the SOC and the reference capacity:

$$Q_{rem} = Q_n \times SOC / 100, \quad Q_{used} = Q_n - Q_{rem} \quad (4)$$

3.4. State of Health, Range and Charging Time

The SOH is a capacity-based figure, the ratio of the measured capacity of the pack to its reference capacity:

SOH = (Q_meas / Q_n) × 100 (5)

In the firmware Q_meas = 2.030 Ah, obtained from a separate capacity measurement of the pack, and Q_n = 2.2 Ah, which gives SOH = 92.27 %. This value is a fixed reference in the current version and is not updated during operation. The remaining range is a demonstration estimate that scales a full-charge range of 60 km with the SOC:

Range = 60 × SOC / 100 (km) (6)

When a charging current larger than 0.05 A is detected, the charging time is estimated as the capacity still needed divided by the charging current:

t_charge = (Q_n − Q_rem) / |I_charge| (h) (7)

3.5. Thermal Management

The cooling fan is controlled with hysteresis. It is switched on when the pack temperature reaches 35 °C and switched off when it falls to 32 °C. The 3 °C band prevents the fan from toggling rapidly around a single threshold. The status is reported as COOLING while the fan is running and NORMAL otherwise.

Table 3. Main firmware parameters.

Parameter	Value
Full / empty pack voltage	12.6 V / 8.4 V
Voltage sensor ratio	5.0
Sensor update interval	2 s
SOC smoothing factor	0.25
SOC save interval	60 s
Reference / measured capacity	2.2 Ah / 2.030 Ah
Fan ON / OFF temperature	35 °C / 32 °C
Full-charge range (demonstration)	60 km
Wi-Fi access point	SmartBMS_ESP32, 192.168.4.1

3.6. Wi-Fi Interface and Mobile Application

The ESP32 operates as a Wi-Fi access point, so no external router or internet connection is required. A web server on port 80 returns a JSON message at the address 192.168.4.1/api/data containing the voltage, current, power, temperature, SOC, voltage-based SOC, SOH, range, charging time, remaining and consumed capacity, fan state and status. The mobile application connects to the access point, reads this message and presents it on five screens: Home, Analytics, Cells, Alerts and Settings. The Home screen shows a status strip (SOH, protection status and connection address) followed by the live battery metric cards, as shown in Figure 2.

4. Results and Discussion

This section presents the operating snapshot of the prototype, captured from the Home screen of the mobile application. Figure 2 shows the live metrics. The values are single readings taken at one operating point and are not averages of a test campaign.

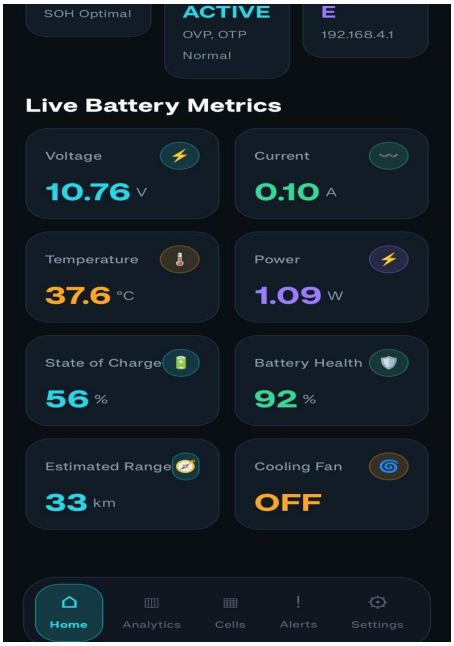


Figure 2. Home screen of the mobile application showing the live battery metrics received from the ESP32 over Wi-Fi.

4.1. Observed Readings

Table 4 lists the values displayed in Figure 2 and the expected value calculated from the firmware equations.

Table 4. Readings displayed by the mobile application at the recorded operating point.

Quantity	Displayed	Check against firmware equations
Voltage	10.76 V	Measured by the voltage sensor
Current	0.10 A	Measured by the INA219
Power	1.09 W	10.76 V × 0.10 A ≈ 1.08 W (current rounded in display)
Temperature	37.6 °C	Measured by the DS18B20
SOC	56 %	(10.76 − 8.4)/4.2 × 100 = 56.2 %
Battery health (SOH)	92 %	2.030/2.2 × 100 = 92.27 %
Estimated range	33 km	60 × 0.56 = 33.6 km
Cooling fan	OFF	–

4.2. Discussion

The SOC shown by the application, 56 %, agrees with Equation (2) for the displayed pack voltage of 10.76 V, which confirms that the application presents the value computed by the firmware. The SOH of 92 % is the capacity ratio of Equation (5), and the range of 33 km follows from Equation (6). The power of 1.09 W is consistent with the product of the displayed voltage and current, the small difference being due to the two-decimal rounding of the current. The status strip shows SOH Optimal, a protection indicator with over-voltage and over-temperature protection reported as active and normal, and the connection address 192.168.4.1, which is the access point address of the ESP32.

Several points should be kept in mind when reading these results. First, the SOC is derived from the pack voltage, which is affected by load and by the rest time of the cells, so it is an approximation and is most reliable when the current is small, as in this snapshot. Second, the SOH is a stored capacity reference and does not yet track ageing during operation. Third, the range is a scaled demonstration figure and does not model the load of a real vehicle. Fourth, the temperature of 37.6 °C is above the 35 °C fan-on threshold while the fan indicator reads OFF in this snapshot; the fan control path and the display refresh should therefore be re-checked and re-captured with the fan running. Finally, if the INA219 is placed only in the fan branch, it measures the fan current and not the total battery current, so it must be placed in series with the load or charger to give the battery current used for power and charging-time estimates.

5. Conclusion

An IoT based smart battery management system for a 12 V lithium-ion pack was designed around the ESP32-C6, with sensing of voltage, current and temperature, voltage-based SOC estimation, a capacity-based SOH reference, range and charging-time estimates, hysteresis fan control, and a Wi-Fi/JSON link to a mobile application. In the recorded snapshot the application displayed 10.76 V, 0.10 A, 1.09 W, 37.6 °C, 56 % SOC, 92 % SOH and a 33 km range, and the SOC, SOH, range and power values are consistent with the firmware equations. The evidence presented covers one operating point and does not yet include charge–discharge profiles, protection cut-off tests or accuracy against a reference instrument.

Future work includes validating the SOC against a reference over full charge–discharge cycles, adding coulomb counting with periodic voltage correction, updating the SOH from measured capacity, placing the current sensor in the main battery path, adding cell-level voltage sensing and balancing, implementing and testing over-voltage, under-voltage and over-temperature cut-off, and logging the data for the Analytics screen.

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