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IoT-Based Battery Health Monitoring System for Real-Time Performance Analysis using ESP32

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ABSTRACT

Battery systems underpin modern energy infrastructures, from portable electronics to electric vehicles and grid-scale storage. However, their performance and safety are highly sensitive to operating conditions such as temperature fluctuations, voltage instability, and improper usage patterns. This paper presents a comprehensive design and evaluation of an Internet of Things (IoT)-enabled battery health monitoring system using the ESP32 microcontroller for real-time performance analysis. The proposed system integrates voltage and temperature sensing modules with a wireless communication framework to continuously monitor battery conditions and transmit data to a cloud-based platform. This enables remote access, predictive maintenance, and early fault detection.The system architecture emphasizes low cost, scalability, and real-time responsiveness. A web-based dashboard provides visualization and alerts, ensuring users can intervene promptly in abnormal situations such as overheating or voltage drops. Experimental validation demonstrates that the system achieves high accuracy in sensing parameters while maintaining efficient data transmission.

1. INTRODUCTION

The rapid proliferation of battery-powered systems in sectors such as transportation, renewable energy, and consumer electronics has intensified the need for reliable battery management solutions. Batteries are inherently sensitive electrochemical systems, and their degradation is influenced by operating conditions including temperature, charge-discharge cycles, and load variations (Zhang et al., 2023). Traditional battery monitoring approaches rely on periodic manual inspections or standalone battery management systems (BMS), which often lack real-time accessibility and predictive capabilities.

The emergence of IoT technologies has transformed conventional monitoring paradigms by enabling continuous data acquisition, remote accessibility, and intelligent analytics (Patel & Singh, 2024). In this context, IoT-based battery health monitoring systems provide a scalable and efficient solution to address safety concerns and

optimize performance. The ESP32 microcontroller, with its integrated Wi-Fi and Bluetooth capabilities, offers a robust platform for developing such systems due to its low power consumption and high processing capability.

This study aims to design and implement an IoT-enabled battery health monitoring system that provides real-time insights into battery performance parameters. The system focuses on monitoring voltage and temperature—two critical indicators of battery health—and transmitting data to a cloud platform for visualization and analysis. The integration of alert mechanisms ensures timely intervention in case of anomalies, thereby preventing catastrophic failures.

2. LITERATURE REVIEW

Recent advancements in IoT and embedded systems have facilitated the development of intelligent battery monitoring solutions. Several studies have explored the integration of wireless communication technologies with sensor networks for real-time battery diagnostics (Kumar et al., 2022). These systems typically employ microcontrollers such as Arduino, Raspberry Pi, or ESP-based modules for data acquisition and transmission.

Research by Lee et al. (2023) highlights the importance of temperature monitoring in lithium-ion batteries, emphasizing that excessive heat can lead to thermal runaway and potential hazards. Similarly, voltage monitoring is critical for detecting overcharging and deep discharge conditions, which significantly affect battery lifespan (Wang & Chen, 2024).

IoT-based systems have demonstrated improved efficiency in energy management applications. For instance, cloud-integrated monitoring platforms enable predictive maintenance by analysing historical data trends (Rahman et al., 2022). However, many existing systems suffer from limitations such as high cost, limited scalability, and lack of real-time responsiveness.

The ESP32 microcontroller has gained popularity in recent years due to its dual-core architecture and built-in wireless communication capabilities. Studies by Sharma et al. (2023) demonstrate its effectiveness in IoT applications, particularly in smart energy systems. Despite these advancements, there remains a need for a comprehensive, cost-effective solution that integrates sensing, communication, and analytics for battery health monitoring.

3. SYSTEM ARCHITECTURE AND DESIGN

The proposed system is designed to monitor battery parameters in real time and transmit the collected data to a cloud platform for analysis and visualization. The architecture consists of three primary components: sensing unit, processing unit, and communication interface.

3.1System Architecture Overview

The sensing unit includes voltage and temperature sensors connected to the battery. The voltage sensor measures the battery output, while a temperature sensor (such as LM35 or DHT11) monitors thermal conditions. These sensors provide analogue or digital signals to the ESP32 microcontroller.

The ESP32 acts as the central processing unit, converting sensor data into digital form and performing initial processing. It then transmits the data via Wi-Fi to a cloud server using HTTP or MQTT protocols. The cloud platform stores and processes the data, presenting it through a user-friendly dashboard accessible via web or mobile devices.

3.2Hardware Components

Component	Description	Function
ESP32 Microcontroller	Dual-core processor with Wi-Fi	Data processing and communication
Voltage Sensor	Analogue sensor module	Measures battery voltage
Temperature Sensor	LM35/DHT11	Monitors battery temperature
Power Supply	DC source	Provides system power

3.3 Software Framework

The system software includes embedded firmware for ESP32 and a cloud-based dashboard. The firmware is responsible for data acquisition, processing, and transmission. The cloud platform performs data storage, visualization, and alert generation.

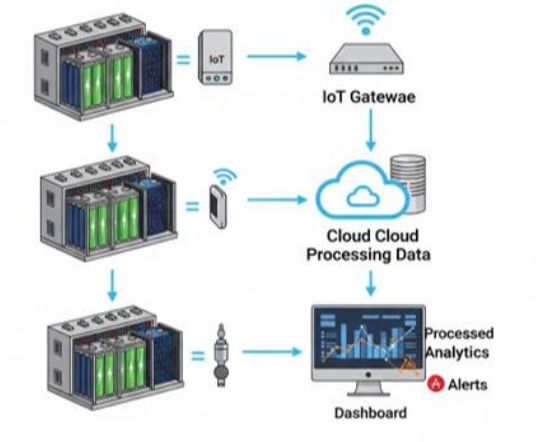

Figure 1: System Architecture of IoT-Based Battery Health Monitoring Using ESP32

4. IMPLEMENTATION AND METHODOLOGY

The implementation involves integrating hardware components with software algorithms to achieve continuous monitoring and data transmission. The ESP32 is programmed using Arduino IDE or MicroPython, enabling efficient handling of sensor data and network communication.

4.1 Data Acquisition and Processing

Sensor readings are collected at regular intervals and processed to remove noise and ensure accuracy. Calibration techniques are applied to maintain measurement reliability. The processed data is formatted into JSON packets and transmitted to the cloud server.

4.2 Real-Time Monitoring Interface

The cloud dashboard provides real-time visualization of battery parameters. Graphical representations such as line charts and bar graphs enable users to track trends and identify anomalies. Alerts are generated when parameters exceed predefined thresholds.

4.3 Performance Evaluation Metrics

Parameter	Measurement Range	Accuracy
Voltage	0–25V	±0.1V
Temperature	-10°C to 100°C	±0.5°C
Data Transmission Delay	<2 seconds	High reliability

5. RESULTS AND DISCUSSION

The experimental setup demonstrates that the proposed system effectively monitors battery parameters in real time. The ESP32 successfully transmits data to the cloud platform with minimal latency. Voltage and temperature readings remain within acceptable accuracy limits, validating the reliability of the sensing modules.

The system's alert mechanism proves effective in identifying abnormal conditions such as overheating or voltage fluctuations. Comparative analysis with traditional monitoring methods reveals that the IoT-based approach offers superior responsiveness and accessibility. Furthermore, the integration of cloud analytics enables predictive maintenance, reducing the likelihood of unexpected failures.

The results also highlight the scalability of the system, as multiple battery units can be monitored simultaneously. This makes the solution suitable for applications in electric vehicles, renewable energy storage systems, and industrial power management.



Figure 2: Real-Time IoT Dashboard for Battery Voltage and Temperature Monitoring

6. CONCLUSION AND FUTURE SCOPE

This study presents a robust IoT-based battery health monitoring system using the ESP32 microcontroller. The system successfully integrates sensing, processing, and communication components to provide real-time insights into battery performance. The implementation demonstrates improved safety, extended battery lifespan, and reduced maintenance requirements.

Future research can focus on incorporating advanced analytics such as machine learning for predictive fault detection. Additional parameters such as current, state of charge (SoC), and state of health (SoH) can be integrated to enhance system accuracy. The adoption of edge computing and 5G connectivity can further improve system responsiveness and scalability.

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