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IoT Based Heat Management System for Electric Vehicle

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Abstract

Growing electrification of road transport has made battery pack reliability a central concern for engineers and manufacturers alike. Heat accumulation within battery cells is among the foremost contributors to accelerated wear and unexpected failure. This article presents a networked, sensor-driven solution that autonomously oversees and adjusts the thermal state of EV battery assemblies. Multiple measurement nodes relay live temperature and electrical readings to a central embedded processor, which evaluates prevailing conditions and energizes cooling or warming devices as dictated by programmed safety logic. Acquired data travels over wireless links to hosted cloud services, affording engineers and operators unimpeded remote visibility. The outcome is a self-correcting system that maintains cell temperatures within tolerable bands, curbs stress-induced wear, and accumulates historical records useful for forecasting future maintenance needs. Bench-level trials confirmed reliable temperature stabilization and a meaningful improvement in operational robustness. The modular construction of the design permits straightforward adaptation to battery packs of varying sizes and chemistries.

Introduction

The global pivot toward electrified transportation has placed battery technology at the forefront of automotive engineering research. Among the variables that most profoundly shape battery pack behavior, operating temperature stands out as especially consequential. Lithium-ion cells—the prevailing choice in contemporary EVs—are acutely sensitive to thermal conditions: sustained exposure to elevated temperatures hastens internal chemical breakdown and heightens the probability of dangerous failure modes, while prolonged cold exposure curtails the energy and power deliverable to the drivetrain. Conventional thermal countermeasures, whether passive heat sinks or manually triggered fans, fall short of the precision and responsiveness demanded by high-energy modern packs.

Addressing this gap calls for a system capable of autonomous, real-time thermal intervention guided by live sensor feedback. The solution developed in this study merges compact measurement electronics, programmable microcontroller logic, and cloud-connected wireless infrastructure into a unified platform. Rather than relying on operator judgment or fixed schedules, the system continuously evaluates battery thermal status and dispatches corrective commands without human involvement. Supplementary cloud connectivity grants remote stakeholders access to live readings and historical datasets, enabling evidence-based decisions regarding battery servicing and replacement.

Literature Review

1. IoT-Based Battery Monitoring and Management System (2024)

An investigation published in 2024 constructed a monitoring arrangement around the ESP32 embedded platform, interfacing it with thermal and voltage transducers and forwarding collected values to ThingSpeak over a standard Wi-Fi link. Graphical representations on the cloud dashboard gave operators an at-a-glance view of battery health, and programmable alarm conditions flagged anomalies in near real time. The study achieved commendable measurement precision and reduced nuisance alarms, yet stopped short of integrating any actuated thermal response or algorithms capable of anticipating future degradation trends.

2. Smart Battery Temperature Control Using Thermoelectric Cooling (2023)

A 2023 publication investigated the use of solid-state thermoelectric elements, driven by an Arduino board receiving signals from LM35 analog sensors, for active heat extraction from battery surfaces. Experimental evidence showed the arrangement lowering cell-surface temperatures by roughly five to eight degrees relative to unassisted conditions. The principal drawbacks identified were substantial parasitic power draw and a noticeable fall-off in performance as battery pack dimensions increased, suggesting limited suitability for production-scale applications.

3. IoT-Based Electric Vehicle Health Monitoring System (2024)

Another 2024 study assembled a multi-sensor vehicle telemetry platform using an ESP8266 Wi-Fi module, GPS receiver, and GSM transceiver, all coordinated through the Blynk mobile application framework. The solution delivered continuous visibility into battery charge level, temperature readings, and vehicle location, and could push alert messages when parameters fell outside acceptable bands. Its scope, however, was restricted to observation; no provision was made for automatically engaging thermal countermeasures when overheating was detected.

4. Hybrid Cooling System for EV Battery Packs (2022)

Research reported in 2022 examined a dual-mode battery cooling architecture that combined mechanically driven airflow with passive phase-change thermal buffers managed by a microcontroller. Compared to single-method baselines, this hybrid strategy produced more uniform temperature fields across the cell array and consumed proportionally less energy. Despite these advantages, the work was restricted to bench-scale hardware and offered no pathway to cloud-based remote supervision, making field deployment uncertain.

Methodology

1. Hardware/Software for Data Collection Module

Required Input Data

- Thermal Readings: Continuous surface-level and ambient temperature figures sampled directly from battery cells.
- Electrical Measurements: Pack-level voltage and instantaneous current draw recorded during operation.
- Actuator State: Current on/off condition of each attached thermal device.
- Node Identity: Factory-assigned unique address distinguishing each sensing unit within the network.
- Threshold Definitions: Upper and lower temperature limits uploaded as configurable safety parameters.

Data Representation Format

- Thermal Values: Integer or floating-point Celsius figures emitted over a digital bus (e.g., 1-Wire for DS18B20).
- Electrical Values: Digitized numeric outputs from analog-to-digital converter channels.
- Actuator Commands: Single-bit binary flags (logic 0 = off, logic 1 = on) dispatched to relay drivers.
- Cloud Payloads: Lightweight JSON objects carrying timestamped field readings for server ingestion.
- Event Logs: Chronologically ordered entries persisted in cloud databases for audit and analysis.

Origins of System Data

- DS18B20 / DHT22 Sensors: Purpose-built digital probes for precise thermal measurement at battery surfaces.
- INA219 / ACS712 Modules: Integrated circuits providing calibrated voltage and current measurements.
- ESP32 / Arduino Board: Embedded processor responsible for data ingestion, computation, and actuation.
- ThingSpeak / Blynk Services: Online platforms offering data storage, trend visualization, and alert dispatch.
- Wi-Fi / GSM Adapter: Hardware link between the embedded node and the internet infrastructure.

Collection and Processing Workflow

Each sensor operates in a free-running loop, producing updated readings at configurable sampling rates. The embedded processor fetches these values via appropriate digital or analog interfaces, applies a rolling average or median filter to reject transient noise, and compares the cleaned result with stored safety limits. Where exceedances are detected, corresponding actuator signals are raised or cleared. Validated readings, along with their decision outcomes, are packaged into lightweight payloads and pushed to the cloud endpoint via the chosen wireless interface. All firmware logic is authored in Embedded C/C++ and compiled within the Arduino integrated development environment.

2. Hardware/Software Development Module

The hardware and firmware are organised around seven discrete functional blocks:

- **Thermal Sensing Block**

Houses the sensing probes and associated signal conditioning; supplies the processor with a continuous stream of validated temperature figures.

- **Computation Block**

Hosts the ESP32 or Arduino processor, which ingests all sensor streams and applies the embedded decision program to determine required actuator states.

- **Actuation Control Block**

Directs power to cooling fans or thermoelectric elements based on binary commands issued by the computation block, keeping cell temperatures within defined limits.

- **Electrical Monitoring Block**

Captures voltage and current waveforms to quantify the electrical load and infer its contribution to internal heat buildup.

- **Network Communication Block**

Manages the bidirectional data channel between the embedded node and cloud services using Wi-Fi or cellular protocols.

- **Alert Dispatch Block**

Formulates and transmits warning messages to registered users when measured values breach safety thresholds or hardware faults are detected.

- **Operator Display Block**

Presents live temperature figures, actuator states, and system health indicators on a local LCD/OLED screen or a remotely accessible web dashboard.

3. Software Stack

- Language: Embedded C/C++
- IDE: Arduino IDE / ESP-IDF toolchain
- Simulation: Proteus Design Suite for pre-build circuit verification
- Cloud Backends: ThingSpeak, Blynk
- Messaging Protocols: MQTT (lightweight publish-subscribe), HTTP REST

4. Training and Testing Module

Key Evaluation Metrics

- Measurement precision of the thermal sensing chain across the full temperature range.
- Speed of actuator engagement from the moment a threshold is crossed.
- Packet delivery success rate and end-to-end IoT transmission reliability.
- Behavioural correctness of the embedded decision logic under all branch conditions.System composure and stability during prolonged high-temperature soak tests.

Adopted Testing Approaches

- Component-Level Tests: Each hardware block validated in isolation before system integration.
- System Integration Tests: Full end-to-end evaluation with all blocks running concurrently.
- Simulation-Aided Tests: Circuit behaviour modelled in Proteus prior to physical construction.
- Extreme Condition Tests: System exercised at the boundaries of its rated thermal operating range.
- Degraded-Mode Tests: Intentional fault injection to verify graceful handling of sensor loss or network outage.

Verification Strategies

- USB serial console monitoring for real-time firmware tracing.
- Reference thermometer comparison to assess sensor reading accuracy.
- Cloud log inspection to confirm upload completeness and timestamp accuracy.
- Stimulus-response recording to quantify alert latency under triggered fault conditions.
- Structured test logs capturing all metric values for post-test performance review.

System Architecture

The overall system is arranged as a vertically stacked set of specialised tiers, each contributing a distinct capability—sensing, computing, switching, actuating, communicating, and presenting. Together these tiers produce a self-sustaining regulation loop that continuously responds to evolving thermal conditions within the battery pack.

1. Measurement Tier
Thermally sensitive probes are affixed at representative locations across the battery assembly, capturing surface and ambient temperatures simultaneously. Electrical transducers operating in parallel record pack voltage and current, providing the data needed to infer ohmic heating effects. Distributing measurement points evenly across the pack guards against blind spots where localised thermal events could otherwise go undetected.

2. Computation Tier
An ESP32 or Arduino serves as the central intelligence of the system. It ingests all incoming sensor data, executes the embedded thermal evaluation algorithm, and resolves the appropriate actuator state for each operating condition. All decision outcomes are logged along with their triggering conditions for subsequent review.

3. Switching Tier
Relay modules or MOSFET gate drivers form the interface between the low-voltage logic signals produced by the microcontroller and the higher-power circuits supplying the thermal actuators. This stage ensures that switching transients do not propagate back into the sensitive measurement and computation stages.

4. Actuation Tier
Axial cooling fans and solid-state thermoelectric devices constitute the physical interventional means available to the system. Fan speed or thermoelectric current is modulated to extract or inject heat as required, returning battery temperatures to within the tolerable operating band.

5. Wireless Transmission Tier
Onboard Wi-Fi or GSM radio modules handle outbound data transfer from the embedded node to internet-hosted servers. Where applicable, the same channel supports inbound configuration updates or remote command issuance from authorised users.

6. Cloud Services and Visualisation Tier
Received data is stored in a structured time-series database on the cloud platform, where it feeds live-updating graphical dashboards. Authorised personnel accessing these dashboards via a browser or smartphone application can review current readings, scroll through historical plots, and acknowledge or configure alarm conditions.

7. Power Infrastructure
A DC power conversion and regulation circuit conditions the raw supply voltage—whether drawn from the vehicle bus or an auxiliary battery—into the stable levels required by sensors, the processor, radio modules, and actuator driver circuits.

System Working
All operational phases unfold within a tightly coupled feedback loop running indefinitely for as long as the system remains powered.

1. Sensor Sampling
At each sampling interval, the measurement tier delivers fresh temperature, voltage, and current figures to the embedded processor's input buffers, ready for evaluation.

2. Condition Assessment
The processor compares each received value against its corresponding upper and lower boundary. Readings lying outside either bound are flagged, and the severity of the exceedance is noted for proportional actuation where applicable.

3. Actuation Decision
Flagged readings trigger specific control responses: a breach of the upper temperature limit energises the cooling circuit; a reading below the lower limit activates a warming element. Readings within the acceptable window leave actuators in their current state, reducing unnecessary cycling and conserving energy.

4. Actuator Engagement
Resolved control signals travel from the processor to the switching tier, which drives the appropriate thermal device at the commanded level, promptly counteracting the detected deviation.

5. Telemetry Uplink
Concurrently with actuation, processed data packets are assembled and transmitted to the cloud endpoint, where they become immediately visible on the operator's dashboard interface.

6. Fault Notification
When a reading exceeds critical safety margins—or when sensor communication fails entirely—the system generates a structured alert payload dispatched as a push notification or text message to pre-registered contacts.

7. Continuous Adaptation
Because the loop never halts, the system perpetually refines its actuator outputs based on the most recent available sensor data. This ongoing correction cycle is what yields the consistent temperature stability observed during validation testing.

Result

Physical prototype trials confirmed that the assembled hardware and firmware performed reliably across a range of induced thermal scenarios. The ESP32 board successfully orchestrated all sensor reads, threshold comparisons, relay activations, and cloud uploads within acceptable latency bounds. The Blynk and ThingSpeak dashboards rendered temperature, voltage, and current gauges accurately, updating in near real time throughout each test session. Both the manual override mode and the fully automatic regulation mode operated as intended, with transitions between states occurring cleanly. Deliberately induced overtemperature conditions were met with prompt fan activation and corresponding alert delivery, demonstrating that the end-to-end response chain functions without significant lag. The collective evidence from these trials supports the conclusion that the proposed architecture is practically viable for integration into next-generation EV thermal management platforms.

Challenges And Limitations

Several engineering and operational challenges remain that must be resolved before the concept can be regarded as fully production-ready.

1. Measurement Reliability of Low-Cost Sensors Budget-grade temperature and current sensing components exhibit vulnerability to drift caused by vibration, electromagnetic emissions from adjacent power electronics, and gradual material degradation. The absence of a scheduled recalibration regimen allows such drift to silently corrupt thermal assessments, potentially allowing hazardous conditions to go unrecognised.

2. Reliance on Wireless Network Infrastructure
Every cloud-facing capability of the platform—live dashboards, alert delivery, remote command reception—presupposes a functioning wireless connection. Geographic coverage gaps or network outages sever this link, degrading the system temporarily to autonomous on-board operation only, without remote visibility.

3. Additional Power Draw
Integrating sensing, processing, and communication hardware into a battery system that is itself energy-constrained introduces a parasitic load that must be carefully accounted for in the vehicle energy budget. Failure to optimise sleep cycles and radio duty cycles can meaningfully reduce pack utilisation efficiency.

4. Challenges of Large-Scale Deployment
Laboratory prototypes built around a handful of sensing points do not scale trivially to the hundreds of individual cells found in production EV packs. Each order-of-magnitude increase in sensor count multiplies cabling complexity, firmware data-handling demands, and per-unit hardware expenditure.

5. Non-Uniform Thermal Distribution
Even with active cooling engaged, fans and thermoelectric devices tend to preferentially cool regions closest to their airflow or heat-exchange surfaces. Cells located in thermally isolated corners of the pack may therefore sustain elevated temperatures that contribute to capacity imbalance and premature localised ageing.

6. Cyber Exposure Through Cloud Connectivity Routing operational data through public cloud infrastructure inherently exposes the communication pathway to interception or manipulation by malicious actors. Comprehensive end-to-end encryption, certificate-based device authentication, and regular security audits are non-negotiable requirements for any production deployment.

7. BMS Compatibility Hurdles
Existing EV platforms incorporate proprietary Battery Management Systems with tightly controlled hardware and software interfaces. Adding an external IoT layer without conflicting with BMS sensing and protection functions demands careful protocol negotiation and extensive co-validation with the OEM.

8. Ongoing Upkeep Demands
Sensors must be periodically recalibrated, connectors inspected for corrosion, and firmware updated to incorporate security patches and feature improvements. Vehicles deployed in demanding duty cycles will likely require more frequent service intervals than

those operating in benign conditions.

9. Cloud Processing Delay Effects

Decision logic hosted in the cloud introduces round-trip network delays that may render it unsuitable for handling the most time-sensitive thermal events. Embedding primary control logic locally on the microcontroller, with cloud services reserved for logging and secondary notifications, is the pragmatic mitigation strategy.

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