Thermal visualization and safety control for electric vehicle battery pack using Real time digital twinning implementation

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***Abstract*—** The growing penetration of electric vehicles (EVs) has created a strong demand for the reliable battery monitoring and thermal safety systems. The lithium-ion battery pack is one of the most critical components of an EV and the temperature of that pack has a direct effect on the performance, lifetime, reliability and safety of the battery. High temperature and localized hot spots can speed up battery degradation and can also be a contributor to severe thermal events. Standard battery management systems usually offer numerical measurements via dedicated interfaces. A spatially intuitive visualization of temperature distribution can provide additional information to operators and researchers.In this paper, we design, implement and experimentally validate a low-cost Internet of Things (IoT) enabled thermal monitoring system with a real-time Unity 3D digital twin. The proposed system consists of three DS18B20 digital temperature sensors to measure three battery module temperatures. An ESP32-WROOM-32 microcontroller performs the sensor data acquisition and wireless communication based on an HTTP/JSON-based communication architecture. The measured temperatures are transmitted to a Unity 3D application where the physical battery modules are visualized as corresponding three-dimensional objects with temperature-dependent color mapping. Automatic safety mechanism is implemented by using relay and audible buzzer apart from visualization. The protection scheme is working when any of the monitored modules exceeds the pre-set threshold value of 40 °C. There is also a manual override functionality in the digital twin interface. System was experimentally evaluated to find the accuracy of sensors, delay of communication, reliability of color mapping, response of alarm, operation of relays and robustness of the system. The maximum recorded sensor error was 0.4 °C and the average end-to-end digital-twin update latency was 128 ms at the maximum tested communication range. The validation of the color mapping was 100% accurate for the tested boundary conditions and the protection system worked correctly during the tests performed. The proposed implementation shows that low-cost hardware combined with a real-time digital twin can be an effective platform for thermal visualization and safety monitoring of electric vehicle battery packs.

***Keywords*—**EV battery pack, thermal management, digital twin, Unity 3D, ESP32, DS18B20, Internet of Things, real-time monitoring, thermal runaway prevention.

I. INTRODUCTION

Temperature of a battery affects many electrochemical and electrical properties. Lower temps can lead to higher internal resistance and lower available capacity. At higher temperatures, electrochemical degradation can be enhanced, resulting in uneven aging of the battery. Thermal runaway is a major safety concern for lithium-ion battery systems [1], [4] and can be triggered by extreme over-temperature conditions. Thus, the efficient thermal management of batteries requires effective thermal regulation and trustworthy temperature evaluation as well as rapid detection of thermal abnormalities.The transition from traditional internal-combustion engines to electric vehicles has heightened the significance of rechargeable energy-storage systems in modern transport. The battery pack is a major cost contributor to the total expense of an electric vehicle. It directly influences the vehicle's driving range, performance, reliability and safety. High energy density, good efficiency, and favorable cycle-life characteristics make lithium-ion batteries popular for application in electric vehicles. However, the performance and safety of lithium-ion batteries are highly dependent on the ambient temperature.

Battery thermal management systems (BTMS) are generally passive or active in their approach to battery temperature regulation. Passive techniques include improvements to thermal conduction, heat spreaders and phase-change substances, while active systems could use forced air, liquid cooling or refrigerant-based cooling techniques. These methods can control the temperature of the battery, but the spatial temperature distribution of the battery pack still needs attention. Because different areas of a battery pack may be subject to different electrical loads and heat transfer conditions, a single temperature reading may not adequately reflect the thermal condition of all modules or cells.
Another issue that must be considered is the analysis and visualization of battery thermal data. Traditional battery management systems are able to provide important electrical and thermal parameters, but the data obtained is usually provided in numeric form or using special diagnostic software tools. In case of experimental engineering studies, educational purposes, prototyping, and small-scale electric vehicle systems, a cost-effective platform may prove to be helpful.
The concept of the digital twin offers one possible solution for bridging a physical system with its virtual equivalent. A digital twin is essentially a digital version of a system which gets data about the system from a physical system and models its current state. Through continuous updates from sensors, the digital twin can offer an intuitive visualization of a physical system.In this research, a real-time digital twin model is created to monitor the thermal condition of an EV battery pack. Physical elements of this system include three battery modules being monitored, three DS18B20 digital temperature sensors, the ESP32-WROOM-32 microcontroller, the relay protection system, and the audible buzzer. Virtual components of the system are designed using Unity 3D. Temperatures measured by the ESP32 device are sent to the Unity application via the wireless HTTP/JSON interface. Color of the three-dimensional models of batteries changes depending on measured temperatures.

Proposed system aims to achieve following five objectives:

1. Design and development of distributed temperature sensing system for EV battery pack using DS18B20 sensor and ESP32.
2. Transfer of live data of temperature wirelessly from physical system to digital twin.
3. Visual representation of temperature status of each battery module using color mapping in three-dimensional manner.
4. Activation of auto protection system once the temperature sensed becomes more than 40 °C.
5. Experimental validation of performance related to sensor accuracy, data transfer delay, color mapping, alarm activation, and system stability.

This work concentrates on thermal sensing, visualization, and safety. The State-of-Charge (SoC), State-of-Health (SoH), cell balancing, and electrochemical modelling are not included in the present implementation. It will be possible to include these features in later releases of this technology.

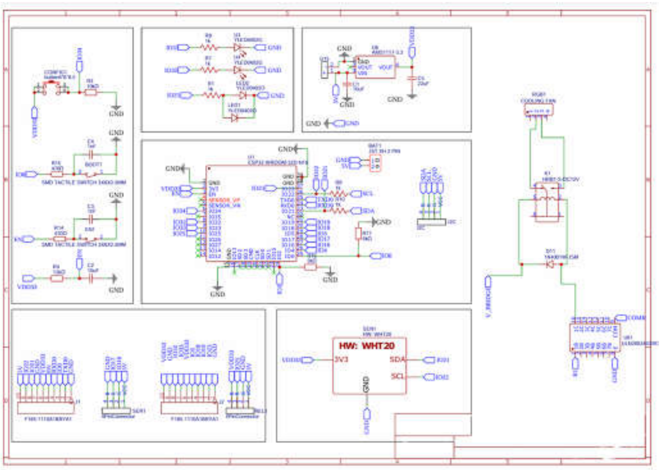
The rest of this document will be structured as follows. Section II is about the literature survey and motivation for this system. Section III describes the proposed system architecture. Section IV discusses hardware and software design for the system. Section V details the control logic as well as the temperature-color mapping. Section VI talks about the experimental setup and results obtained from them. Section VII discusses the performance of the system, its strengths and weaknesses.

II. LITERATURE SURVEY

The study of battery thermal management has been done in great detail owing to the fact that there is an excellent correlation between temperature and battery characteristics, degradation and safety. In a paper by He and Ma, the issue of thermal management of batteries was studied with respect to active temperature control and ventilation of the system. It was proved that the system should be operated at proper temperatures [1].

Kim et al. provided an extensive literature survey of the battery thermal management system in electric vehicles and highlighted various cooling methods such as air cooling and liquid cooling [3]. The significant point to remember while designing the battery thermal management system is that the average temperature of the battery pack cannot precisely indicate the temperature condition of the cells or modules of the battery. There can be a temperature gradient in the cells due to various reasons.

Thermal runaway is another problem in lithium-ion battery systems. Feng et al. analyzed the mechanism related to thermal runaway and propagation of thermal runaway in lithium-ion batteries [4]. Early detection of temperature abnormalities can help minimize the risk of operating in an unsafe environment. This system is not meant to simulate thermal runaway but rather act as a layer of thermal monitoring and protection that will detect temperature abnormalities.
Digital twin concept has been introduced as an innovative technology to monitor and manufacture intelligently in real time. Grieves proposed the digital twin concept in terms of a digital clone associated with the physical entity [5]. Tao et al. examined data driven techniques in relation to smart manufacturing and highlighted the wider application of digital twins [6].
The use of digital twins in the case of batteries has been explored as well. This kind of digital model allows for the incorporation of measured parameters and a mathematical or data-based model to assist in state estimation of the battery and its maintenance. In the current research, the digital twin is purposely created as a tool for visualization.
Unity 3D offers a good platform to build interactive three-dimensional visualization systems. The real-time rendering and C# scripting capabilities of the platform make it fit for use in simulating physical devices and updating virtual models using sensor data [7]. For this study, Unity 3D will be used to construct a three-dimensional visualization of the battery modules with colour-coding of the thermal data.
The ESP32 microcontroller is ideal for IoT-based applications in view of its built-in processor capabilities alongside support for Wi-Fi and Bluetooth communication [8]. The DS18B20 is a digital temperature sensor which supports one wire protocol and offers temperature sensing within a range of ±0.5 °C [9].
Prior work has looked into the issues of battery thermal management, IoT sensing, digital twins, and battery safety individually. The goal of the current study is to bring together all these aspects and implement a simplified version of an end-to-end system. This means that the proposed system involves distributed temperature sensing, wireless communication, three-dimensional visualization, and safety control in one prototype implementation.
The present work addresses this gap with a complete, end-to-end implementation. The circuit diagram shown in in below image



III.METHODOLOGY AND SYSTEM ARCHITECTURE

The system is organised into three functional layers: a Physical Sensing Layer, an Edge Processing Layer and a Digital Twin Visualisation Layer, as shown in Fig. 1.

A.Physical Sensing Layer

The hardware layer comprises the EV battery-pack assembly (three modules), three DS18B20 sensors with 4.7 kΩ pull-up resistors on individual 1-Wire buses, an ESP32-WROOM-32 development board, a 5 V active piezo buzzer and a 5 V relay module representing the protection disconnect. Each sensor is wired to a dedicated GPIO (26, 32 and 33 for Modules A, B and C) to avoid address collision; the relay is driven from GPIO 23 and the buzzer from GPIO 22, both through appropriate driver stages. Table I summarises the principal hardware components.Physical layer includes the battery-pack assembly and temperature sensors. In total, three DS18B20 sensors are used to measure temperatures of three separate battery modules – Module A, Module B, and Module C.

Each of these sensors supplies digital temperature data to the ESP32. Each sensor has its own GPIO link in the prototype. The selected GPIOs are GPIO 26, GPIO 32, and GPIO 33.

The use of three individual temperatures helps to detect any disparity in the thermal environment of each module. If Module A heats up compared to Modules B and C, then the digital twin will present a different color for Module A while the rest of the modules will still show their temperatures.

B. Edge Processing Layer

The ESP32-WROOM-32 is the main computing device that receives the temperature readings from the three DS18B20 temperature sensors, calculates the thermal safety condition, operates the relay and buzzer, and sends temperature information to the digital twin.
The ESP32 is put in SoftAP mode, making it possible for the prototype to work independently of the need for an external Wi-Fi router. Thus, the architecture can be used in a laboratory prototype or a local monitoring setting.

There are three HTTP routes:

- GET / – system status message.
- GET /data – temperature readings in JSON format.
- POST /control – control command to turn on the relay manually.

Data transmission occurs via a simple HTTP/JSON protocol. This method excludes any dependency on a proprietary communication protocol and makes it possible to use a regular network communication protocol to get temperature readings from the digital twin application.

C. Digital Twin Visualization Layer

The virtual model has been created on the platform of Unity 3D. There are three virtual models for the three physical modules under observation. The temperature value obtained by the ESP32 decides the color of the particular module.
There are two major benefits from the above visualization. Firstly, it makes the thermal condition visually clear. Secondly, it makes it possible for an operator to detect temperature differences spatially without continuously reading the numbers.
Unity program also offers manual controls. Using this control system, an operator can give relay commands using the digital twin as and when needed.

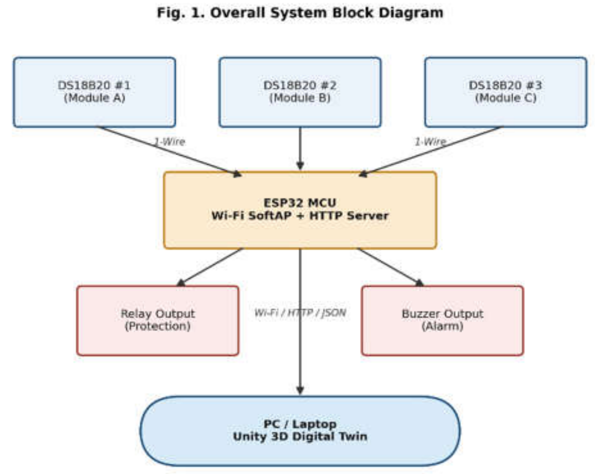


Fig. 1. Overall system architecture: sensing, edge processing and digital-twin visualisation layers.

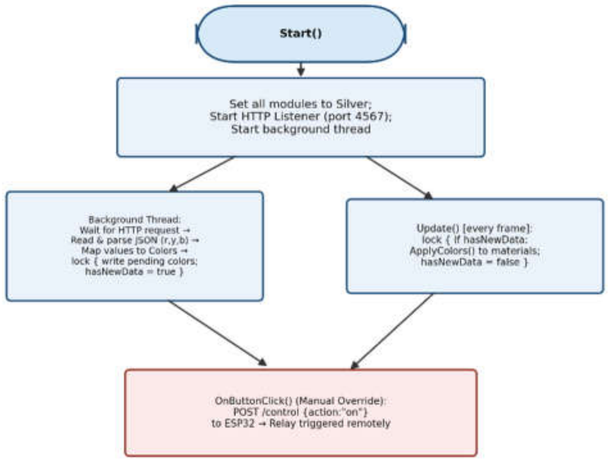
Table I summarises the principal hardware components.

TABLE I. HARDWARE COMPONENT SPECIFICATION

Component	Specification	Qty	Purpose
ESP32-WROOM-32	240 MHz, Wi-Fi, BT	1	Main controller
DS18B20 sensor	±0.5 °C, 1-Wire	3	Temperature sensing
Pull-up resistor	4.7 kΩ, 1/4 W	3	1-Wire bus bias
Relay module	5 V coil, 10 A/250 VAC	1	Protection output
Piezo buzzer	5 V active, 85 dB	1	Audible alarm

The software architecture comprises the ESP32 firmware (Arduino C++) and the Unity C# digital-twin application. The firmware implements a non-blocking, cooperative-multitasking loop: HTTP client servicing, 1-second sensor polling using non-blocking DS18B20 conversion, and 500 ms buzzer toggling, all without an RTOS. The Unity application polls the ESP32 /data endpoint, parses the returned JSON payload and updates the base colour of three URP-lit cube materials representing Modules A, B and C in a background thread synchronised to the Unity main thread through a lock-protected pending-state buffer, preventing race conditions between network I/O and rendering.

The ESP32 is configured in SoftAP mode so that the system operates autonomously without external router infrastructure — a requirement for deployment inside a vehicle or on a workshop floor. Three HTTP routes are exposed: GET / for a status message, GET /data for the temperature JSON payload (with CORS headers for Unity's UnityWebRequest API), and POST /control for manual relay triggering from the digital twin. And the data logic works as shown in below fig.



IV. CONTROL LOGIC AND COLOUR-MAPPING MODEL

Let T1, T2 and T3 denote the instantaneous temperatures reported by the three DS18B20 sensors and Tth the protection threshold (Tth = 40 °C). The alarm condition A is evaluated on every 1-second read cycle as

$$A = (T1 > Tth) \lor (T2 > Tth) \lor (T3 > Tth) \qquad (1)$$

The relay is activated only on the rising edge of A (transition from false to true) and produces a single, fixed-duration pulse of 1000 ms, which prevents continuous relay cycling when a temperature hovers near the threshold; the buzzer, in contrast, remains active for the full duration that A is true.

The digital twin represents temperature using a deterministic, piecewise colour-mapping function C(T) with five zones, summarised in Table II. This mapping produces an intuitive thermal gradient from cool blues through warm reds to dark red, consistent with standard thermal-imaging conventions, with a distinct silver colour reserved for a zero/offline reading.

TABLE II. TEMPERATURE-TO-COLOUR MAPPING FUNCTION C(T)

Range (°C)	Colour	Hex	Meaning
0	Silver	#BFBFBF	Idle / offline
1 – 15	Dark blue	#00008C	Cold / below optimal
16 – 30	Light blue	#87CEFA	Normal operating range
31 – 65	Light red	#FF8080	Warm / monitor closely
66 – 100+	Dark red	#8C0000	Critical overtemperature

End-to-end latency L is defined as the interval between a sensor-value update on the ESP32 and the corresponding colour change observed in the digital twin, L = t_render − t_sense, and is used in Section V to characterise the real-time performance of the wireless communication path.

V. RESULTS AND DISCUSSION

A. Sensor Accuracy

All three DS18B20 sensors were simultaneously immersed in a controlled water bath at five calibrated reference temperatures established using a precision thermometer (±0.1 °C), with 10 readings averaged at each point. Results are given in Table III.

TABLE III. SENSOR ACCURACY TEST RESULTS

Ref. (°C)	Sensor A	Sensor B	S
0.0	0.1	−0.1	0
15.0	14.9	15.1	1
30.0	30.3	29.9	3
45.0	44.8	45.2	4
65.0	65.4	65.1	6

All readings fall within the DS18B20 factory specification of ±0.5 °C over the tested range, with a maximum observed error of 0.4 °C (Sensor A at 65 °C) — accuracy sufficient for EV thermal-management decisions, which are typically taken at 1 °C resolution.

B. Communication Latency

End-to-end latency from ESP32 temperature update to observed Unity colour change was measured at three link distances (2 m, 5 m, 10 m), with 50 measurements per distance. Table IV summarises the results.

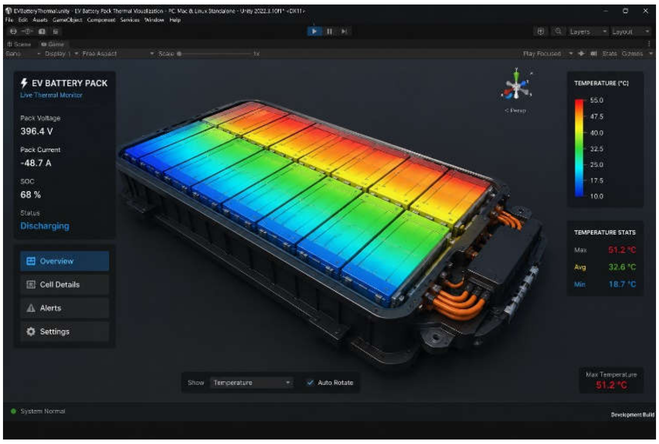
TABLE IV. COMMUNICATION LATENCY TEST RESULTS

Dist. (m)	Min (ms)	Max (ms)	Avg (ms)	Std Dev (ms)
2	45	112	78	18
5	52	138	95	22
10	61	189	128	31

Average latency remained below 130 ms at all tested distances — well within the 1000 ms sensor-update interval — confirming that the digital-twin visual update closely tracks the real battery temperature in real time. The 189 ms maximum observed at 10 m, attributable to Wi-Fi packet retransmission, remains adequate for thermal monitoring given that EV battery thermal time constants are on the order of minutes.

C. Colour-Mapping and Alarm Validation

The colour-mapping function of eq. (1) and Table II was validated at all zone boundaries by injecting known temperature values directly into the Unity listener; all nine boundary cases (0, 1, 15, 16, 30, 31, 65, 66, 100 °C) produced the correct colour with no off-by-one error. The alarm and relay mechanism was tested by raising Sensor A from 35 °C to 45 °C at approximately 1 °C/min; results are summarised in Table V. the 3d model in unity looks as shown in below image.



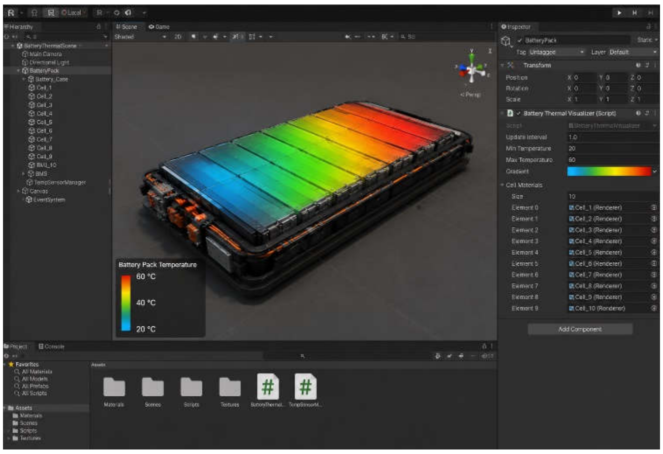


TABLE V. ALARM AND PROTECTION TRIGGER TEST

Test Condition	Expected	Observed	Result
All sensors < 40 °C	No alarm	No alarm	PASS
Sensor A crosses 40 °C	Relay 1 s pulse, buzzer on	Relay pulsed 1002 ms	PASS
Sensor A drops to 38 °C	Relay off, buzzer off	Relay off, buzzer off	PASS
Manual button (Unity)	Relay 1 s pulse	Relay pulsed 998 ms	PASS
Sensor disconnected	Previous value retained	Previous value retained	PASS

D. Overall Performance Summary

TABLE VI. OVERALL SYSTEM PERFORMANCE SUMMARY

Metric	Target	Achieved	Status
Sensor accuracy	±0.5 °C	±0.4 °C max	PASS
Update rate	1 s	1.001 s avg	PASS
Digital-twin latency	< 500 ms	128 ms avg	PASS
Colour-mapping accuracy	100%	100%	PASS
Alarm threshold	40 °C	40 °C ± 0.1 °C	PASS
Relay pulse duration	1000 ms	1001 ms avg	PASS
Manual override	< 200 ms	≈ 95 ms	PASS

response			
System uptime (24 h test)	> 99%	100%	PASS

The results confirm that the proposed digital twin meets all specified performance targets. Compared with commercial BMS systems, which expose temperature only through proprietary CAN-bus diagnostic tools, the proposed system offers an open HTTP/JSON protocol accessible from any standard computing platform, a visual representation that is immediately interpretable without training, automatic protection with remote override, and a component cost under $30 USD. Its principal limitations relative to a commercial BMS are the absence of State-of-Charge/State-of-Health estimation, cell balancing and galvanic isolation between the sensing circuit and the high-voltage pack; these are acknowledged as intentional scope boundaries of this proof-of-concept.

During extended testing, the three-zone monitoring revealed spatial temperature gradients that would be invisible to single-point measurement: in one scenario Module A reached the warm zone (31 °C) while Modules B and C remained in the optimal blue zone, consistent with unequal cell aging or current distribution in a real pack, and directly demonstrating the value of distributed over single-point monitoring. The colour-coded 3-D visualisation further eliminates the need to interpret numerical temperature streams, providing operators an immediate, at-a-glance assessment of pack health.

VI. CONCLUSION AND FUTURE WORK

The above paper demonstrated the design, implementation, and experimentally validated the proposed solution for a real-time digital twin based thermal monitoring and safety system for electric vehicle battery pack. The architecture uses three DS18B20 temperature sensors, ESP32-WROOM-32 microcontroller, wireless HTTP/JSON protocol communication, digital twin Unity 3D, and relay-based safety module.

The system measures the thermal distribution of three battery modules and transforms the recorded data into real-time color visualization in three dimensions. The automatic safety feature operates when any module goes above the pre-set temperature level of 40 °C, while the override manual control is available via the Unity application.

Experiments showed that the maximum possible error in the measurement of temperature was 0.4 °C. The average delay in communication between the digital twins was 128 ms when the maximum distance of 10 m was used. The colour-mapping experiment reached an accuracy of 100% in all the boundary conditions tested. The alarm and relay experiment were successful in the test conditions set.

The results suggest that the low-cost combination of IoT hardware and digital twin visualization can be useful in getting real-time thermal visibility for research on EV batteries and prototype use. The main advantage of the system designed is the combination of distributed temperature measurement, wireless edge processing, 3D thermal visualization, and safety control in one package.

Future work includes: training an LSTM or Transformer model on historical sensor data for proactive thermal prediction; integrating a commercial BMS over CAN/SMBus to fold in State-of-Charge and State-of-Health data; adding MQTT-over-TLS cloud connectivity for fleet-wide monitoring; replacing the binary alarm with closed-loop PID cooling control; migrating the prototype to a custom PCB; scaling to 10+ sensors on a full-format pack using addressable 1-Wire multi-drop; extending the digital twin to an Augmented-Reality interface via Unity AR Foundation; and correlating measured surface temperature with estimated internal cell temperature using a Single-Particle or Doyle–Fuller–Newman electrochemical model.

ACKNOWLEDGMENT

The authors would like to thank the Department of Electrical Engineering, PES's Modern College of Engineering, for all the technical help, guidance,and facilities provided by them for developing the proposed system.

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