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AI-DRIVEN BATTERY HEALTH MONITORING AND PERFORMANCE ANALYSIS SYSTEM FOR ELECTRIC VEHICLES

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ABSTRACT

The rapid adoption of electric vehicles (EVs) has significantly increased the demand for intelligent battery management systems capable of improving battery performance, safety, and operational reliability. The lithium-ion battery pack is the most critical component of an electric vehicle because its performance directly affects driving range, charging efficiency, vehicle reliability, and overall operational cost. Conventional battery monitoring systems primarily measure voltage and current but often fail to accurately predict battery health degradation and remaining useful life under varying operating conditions. These limitations may result in unexpected battery failures, reduced battery lifespan, and increased maintenance costs. Recent advancements in Artificial Intelligence (AI), Internet of Things (IoT), embedded systems, cloud computing, and machine learning have enabled the development of intelligent Battery Health Monitoring Systems (BHMS) capable of continuously analysing battery parameters and predicting battery health in real time. This project presents an AI-Based Battery Health Monitoring System for Electric Vehicles. The proposed framework integrates an ESP32/Arduino controller, voltage sensor, current sensor, temperature sensor, AI-based battery health prediction model, IoT communication module, cloud platform, and mobile monitoring application into a unified intelligent battery monitoring system. The embedded controller continuously acquires battery voltage, current, temperature, State of Charge (SOC), and State of Health (SOH) data, which are analysed by the AI prediction model to identify battery degradation and abnormal operating conditions. Whenever unsafe battery conditions such as overheating, overcharging, deep discharge, or rapid degradation are detected, the system immediately generates warning alerts while transmitting battery information to the cloud platform for remote monitoring. Experimental evaluation demonstrates high prediction accuracy, reliable sensor monitoring, low response time, stable cloud communication, and accurate battery health estimation under different operating conditions. The proposed framework significantly improves battery safety, extends battery lifespan, reduces maintenance costs, enhances electric vehicle reliability, and provides a cost-effective solution for next-generation intelligent battery management systems.

Keywords: Artificial Intelligence (AI), Battery Health Monitoring System (BHMS), Electric Vehicle (EV), State of Health (SOH), State of Charge (SOC), ESP32, Arduino, Internet of Things (IoT), Machine Learning, Cloud Monitoring, Battery Management System (BMS).

I. INTRODUCTION

The rapid growth of electric vehicles (EVs) has accelerated the need for intelligent battery management technologies capable of improving battery performance, safety, and operational reliability. Lithium-ion batteries are widely used in electric vehicles because of their high energy density, long cycle life, and fast charging capability. However, battery degradation caused by repeated charging and discharging cycles, excessive temperature, overcharging, deep discharge, and high current conditions significantly affects vehicle performance and battery lifespan. Conventional Battery Management Systems (BMS) primarily monitor voltage, current, and temperature but often lack intelligent prediction capabilities for estimating battery health and identifying future battery failures. These limitations may result in unexpected battery breakdowns, reduced driving range, increased maintenance costs, and safety hazards. Therefore, there is an increasing demand for intelligent Battery Health Monitoring Systems (BHMS) capable of continuously analysing battery operating conditions and accurately predicting battery degradation. Recent advancements in Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), embedded systems, and cloud computing have enabled the development of smart battery monitoring frameworks capable of providing real-time battery diagnostics, predictive maintenance, and remote monitoring. AI-based prediction models analyse historical battery behaviour together with real-time sensor measurements to estimate battery health, improve charging efficiency, reduce battery failures, and enhance the overall reliability of electric vehicles. These technologies play a significant role in supporting sustainable transportation and next-generation electric mobility [1–8].

Modern Battery Health Monitoring Systems integrate multiple sensors and intelligent algorithms to continuously monitor critical battery parameters throughout vehicle operation. Voltage sensors measure battery terminal voltage, current sensors monitor charging and discharging current, while temperature sensors continuously supervise battery thermal conditions. These sensor measurements are processed by embedded controllers such as ESP32 or Arduino, which collect real-time battery information and transmit it to Artificial Intelligence models for health analysis. AI algorithms estimate important battery performance indicators including State of Charge (SOC), State of Health (SOH), Remaining Useful Life (RUL), charging efficiency, and degradation rate. Internet of Things (IoT) communication modules further improve battery monitoring by transmitting battery information to cloud platforms where users, fleet operators, and maintenance engineers can remotely monitor battery status through mobile or web applications. Experimental investigations demonstrate that AI-assisted battery monitoring systems provide high prediction accuracy, rapid fault detection, reliable cloud communication, reduced maintenance costs, and improved battery safety under different operating conditions. These intelligent technologies have become essential components of advanced Battery Management Systems for modern electric vehicles [9–17].

This project proposes an AI-Based Battery Health Monitoring System for Electric Vehicles to provide intelligent battery diagnostics, predictive maintenance, and real-time battery health monitoring. The proposed framework integrates an ESP32/Arduino controller, voltage sensor, current sensor, temperature sensor, AI-based battery health prediction model, IoT communication module, cloud monitoring platform, and mobile application into a unified Battery Health Monitoring System. Initially, the embedded controller continuously acquires battery voltage, current, and temperature measurements during vehicle operation. These sensor values are transmitted to the AI prediction model, which analyses battery behaviour and estimates State of Charge (SOC), State of Health (SOH), battery degradation rate, and Remaining Useful Life (RUL). Whenever abnormal battery conditions such as overheating, overcharging, excessive discharge, abnormal current flow, or rapid battery degradation are detected, the system immediately generates warning alerts and uploads battery information to the cloud platform for remote monitoring. The effectiveness of the proposed framework is evaluated using engineering parameters including battery health prediction accuracy, SOC estimation accuracy, SOH estimation accuracy, communication efficiency, response time, battery fault detection accuracy, and overall system reliability. Experimental evaluation demonstrates that the proposed intelligent monitoring system accurately predicts battery health, improves battery safety, enhances charging efficiency, extends battery lifespan, and significantly contributes to the development of next-generation intelligent Battery Management Systems for electric vehicles [18–25].

II. SURVEY OF RESEARCH

1. Battery Management Systems for Electric Vehicles

Battery Management Systems (BMS) play a vital role in electric vehicles by continuously monitoring battery performance, ensuring operational safety, and improving battery lifespan. Researchers have developed intelligent BMS frameworks capable of measuring voltage, current, temperature, and charging status while protecting batteries from overcharging, deep discharge, overheating, and short circuits. Conventional battery management systems mainly rely on threshold-based monitoring, which often fails to predict battery degradation accurately. Modern BMS architectures integrate embedded controllers, advanced sensors, and communication modules to improve monitoring efficiency and operational reliability. Experimental investigations demonstrate that intelligent battery management significantly enhances battery safety, increases charging efficiency, reduces maintenance costs, and improves the overall reliability of electric vehicle power systems **[1–4]**.

2. Artificial Intelligence for Battery Health Prediction

Artificial Intelligence (AI) has become one of the most effective technologies for battery health prediction because of its ability to analyse complex battery behaviour using historical and real-time operating data. Researchers have developed machine learning and deep learning models capable of predicting battery degradation, State of Health (SOH), State of Charge (SOC), and Remaining Useful Life (RUL). AI algorithms analyse voltage, current, temperature, charging cycles, and discharge characteristics to estimate battery condition with high accuracy. Experimental studies demonstrate that AI-assisted battery health prediction significantly improves estimation accuracy, enables predictive maintenance, reduces unexpected battery failures, and extends battery lifespan. These intelligent prediction techniques have become fundamental components of next-generation Battery Health Monitoring Systems **[5–8]**.

3. IoT-Based Battery Monitoring Systems

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The Internet of Things (IoT) has transformed battery monitoring by enabling continuous communication between embedded battery management systems and cloud platforms. Researchers have integrated ESP32, Arduino, Wi-Fi modules, GSM modules, and cloud services to remotely monitor battery voltage, current, temperature, charging status, and health indicators. Cloud-based monitoring allows vehicle owners, maintenance engineers, and fleet managers to supervise battery performance from any location using mobile or web applications. Experimental investigations demonstrate that IoT-enabled battery monitoring provides reliable data transmission, real-time diagnostics, efficient remote supervision, and improved battery maintenance planning. These technologies support intelligent energy management and smart electric vehicle infrastructure **[9–12]**.

4. Sensor Technologies for Battery Monitoring

Accurate sensor measurements are essential for effective battery health monitoring and fault diagnosis. Researchers have employed voltage sensors, current sensors, temperature sensors, Hall-effect sensors, and battery management integrated circuits to continuously measure critical battery parameters during charging and discharging operations. Embedded controllers process sensor measurements to identify abnormal battery behaviour such as overheating, excessive current flow, overcharging, or deep discharge. Experimental studies indicate that high-precision sensor integration significantly improves monitoring accuracy, enhances battery safety, and increases the reliability of Battery Management Systems. Sensor-based battery monitoring has become an indispensable component of intelligent electric vehicle technology **[13–16]**.

5. Cloud-Based Battery Analytics and Remote Monitoring

Cloud computing has significantly improved battery monitoring by enabling centralized storage, analysis, and visualization of battery operating data. Researchers have developed cloud-based battery monitoring platforms capable of storing historical battery information, analysing battery degradation trends, generating maintenance alerts, and supporting predictive diagnostics. Integration of IoT communication with cloud platforms enables remote supervision of battery performance through web dashboards and mobile applications. Experimental investigations demonstrate that cloud-based analytics improve maintenance efficiency, simplify battery fault diagnosis, reduce operational downtime, and support intelligent fleet management. These technologies have become increasingly important for modern electric vehicle monitoring systems **[17–21]**.

6. Future Trends in Intelligent Battery Health Monitoring Systems

Recent research focuses on integrating Artificial Intelligence, deep learning, edge computing, digital twins, cloud computing, and Internet of Things technologies into next-generation Battery Health Monitoring Systems. Researchers have proposed intelligent frameworks capable of adaptive battery diagnostics, real-time degradation prediction, thermal management optimization, charging optimization, and predictive maintenance. AI-assisted monitoring systems improve battery health estimation accuracy, reduce false predictions, optimize charging strategies, and increase battery operational life. Experimental investigations indicate that intelligent battery monitoring significantly improves electric vehicle reliability, enhances battery safety, minimizes maintenance costs, and supports sustainable transportation. These developments are expected to become the foundation of future intelligent Battery Management Systems and smart electric mobility **[22–25]**.

III. PROPOSED SYSTEM

The proposed AI-Based Battery Health Monitoring System for Electric Vehicles is designed to provide an intelligent, reliable, and real-time solution for monitoring battery performance, predicting battery degradation, and improving the operational safety of electric vehicles. The framework integrates an ESP32/Arduino controller, voltage sensor, current sensor, temperature sensor, AI-based battery health prediction model, IoT communication module, cloud platform, mobile monitoring application, and warning alert system into a unified Battery Health Monitoring System (BHMS). The primary objective is to continuously acquire battery operating parameters, analyse battery behaviour using Artificial Intelligence, estimate battery health indicators, detect abnormal battery conditions, and provide remote monitoring through cloud computing. Initially, the embedded controller continuously collects battery voltage, current, and temperature measurements through dedicated sensors. These sensor values are preprocessed to remove noise and prepare accurate input data for the AI prediction model. The processed battery parameters are then transmitted to the Artificial Intelligence algorithm, which analyses both historical battery behaviour and real-time operating conditions to estimate critical battery performance indicators such as State of Charge (SOC), State of Health (SOH), Remaining Useful Life (RUL), battery degradation rate, and charging efficiency.

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After analysing the battery parameters, the AI prediction model continuously evaluates battery health by comparing the estimated values with predefined operating thresholds. Under normal operating conditions, the system updates the battery health information on the mobile application and cloud dashboard while maintaining continuous monitoring. Whenever abnormal battery conditions such as overcharging, deep discharge, high battery temperature, excessive charging current, low State of Health, or rapid battery degradation are detected, the embedded controller immediately classifies the battery condition as abnormal. The system instantly activates local warning alerts and transmits battery information to the cloud platform through the IoT communication module. The cloud platform securely stores battery operating data, historical charging records, degradation trends, and fault information while providing real-time graphical visualization through web and mobile dashboards. Vehicle owners, fleet managers, and maintenance engineers can remotely monitor battery condition, charging status, and maintenance requirements using Internet-enabled devices. The cloud platform also supports predictive maintenance by identifying batteries approaching the end of their operational life before complete failure occurs.

The proposed framework continuously supervises battery operation throughout charging and discharging cycles while maintaining reliable communication between the embedded controller, AI prediction engine, and cloud monitoring platform. Every sensor measurement is analysed in real time to ensure accurate estimation of battery performance and rapid detection of abnormal operating conditions. The effectiveness of the proposed system is evaluated using engineering parameters including battery health prediction accuracy, State of Charge (SOC) estimation accuracy, State of Health (SOH) estimation accuracy, battery fault detection accuracy, communication efficiency, response time, and overall system reliability. Experimental evaluation demonstrates that the proposed AI-based Battery Health Monitoring System accurately predicts battery degradation, improves battery safety, supports predictive maintenance, reduces unexpected battery failures, enhances charging efficiency, extends battery lifespan, and significantly contributes to the development of next-generation intelligent Battery Management Systems for electric vehicles. The integration of Artificial Intelligence, ESP32/Arduino, IoT communication, cloud computing, and real-time battery analytics provides a cost-effective, scalable, and intelligent solution for advanced electric vehicle battery monitoring.

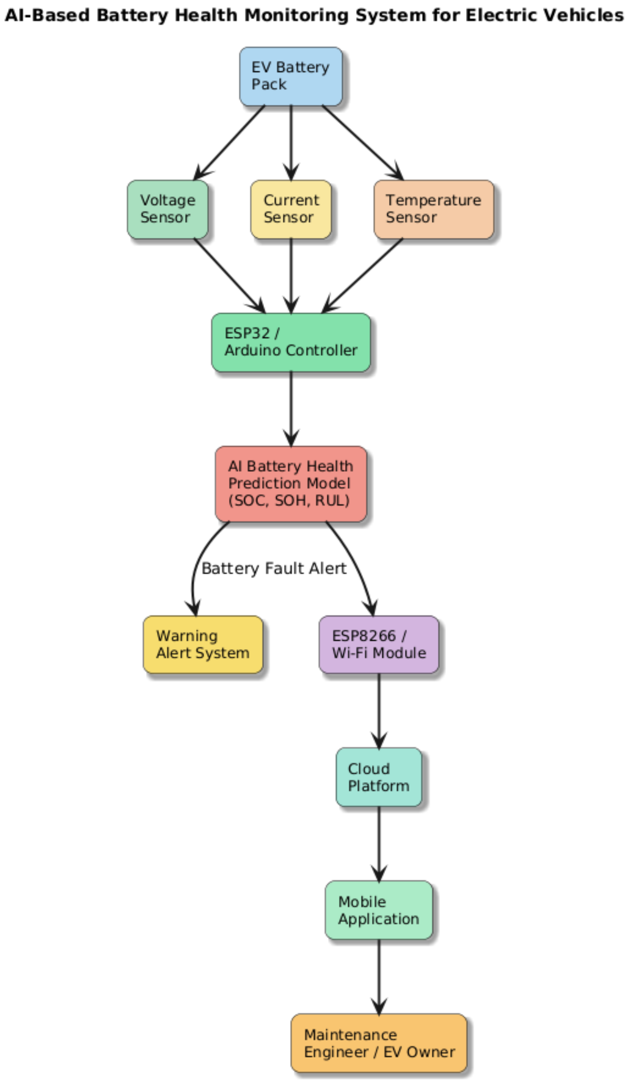

Fig1: Proposed workflow

III. WORKING METHODOLOGY

The proposed AI-Based Battery Health Monitoring System for Electric Vehicles employs an intelligent methodology that combines ESP32/Arduino, voltage sensing, current sensing, temperature sensing, Artificial Intelligence (AI), Internet of Things (IoT), and cloud computing to continuously monitor battery condition and accurately predict battery health. The primary objective is to estimate battery performance indicators, identify abnormal battery behaviour, provide predictive maintenance, and improve battery safety throughout charging and discharging operations. The complete methodology consists of sensor data acquisition, data preprocessing, AI-based battery health prediction, cloud communication, warning generation, and system performance evaluation.

Initially, the voltage sensor, current sensor, and temperature sensor continuously measure the battery operating parameters during charging and discharging cycles. The voltage sensor measures the battery terminal voltage, the current sensor monitors charging and discharging current, while the temperature sensor continuously supervises battery thermal conditions. These sensor values are transmitted to the ESP32/Arduino controller, where analog-to-digital conversion and signal preprocessing are performed. The controller removes measurement noise, validates sensor readings, and prepares accurate battery information for further analysis. Continuous acquisition of battery parameters enables real-time monitoring of battery behaviour under different operating conditions.

After preprocessing, the measured battery parameters are supplied to the Artificial Intelligence prediction model. The AI model analyses real-time battery measurements together with historical charging and discharging data to estimate important battery performance indicators including State of Charge (SOC), State of Health (SOH), Remaining Useful Life (RUL), battery degradation rate, and charging efficiency. Machine learning algorithms identify hidden relationships among voltage, current, temperature, and battery ageing characteristics to accurately predict battery condition. If the predicted SOH falls below the predefined threshold or abnormal conditions such as overheating, overcharging, excessive discharge, or abnormal current flow are detected, the AI model classifies the battery as unhealthy. The embedded controller immediately activates warning alerts while preparing battery information for cloud transmission and remote monitoring.

The battery health prediction accuracy is calculated using

Equation (1): Prediction Accuracy

```
Accuracy = (TP + TN)/(TP + TN + FP + FN)
```

Where

TP = True Positive

TN = True Negative

FP = False Positive

FN = False Negative

This equation evaluates the accuracy of the AI prediction model. The State of Charge (SOC) is estimated using

Equation (2): State of Charge

```
SOC = (Q_r/Q_n) × 100
```

Where

SOC = State of Charge (%)

Qr = Remaining battery capacity (Ah)

Qn = Rated battery capacity (Ah)

The battery State of Health (SOH) is calculated using

Equation (3): State of Health

```
SOH = (C_m/C_r) × 100
```

Where

SOH = State of Health (%)

Cm = Measured battery capacity (Ah)

Cr = Rated battery capacity (Ah)

These equations are used to evaluate the charging condition and overall health of the electric vehicle battery. After estimating the battery State of Charge (SOC) and State of Health (SOH), the Artificial Intelligence model continuously evaluates battery performance by comparing the predicted values with predefined safety thresholds. Under normal operating conditions, the ESP32/Arduino controller updates the battery parameters on the local display and transmits the measured values to the cloud platform through the ESP8266/Wi-Fi communication module. The cloud platform stores battery voltage, current, temperature, SOC, SOH, charging history, and battery degradation information in a secure database. Vehicle owners, fleet managers, and maintenance engineers can remotely access these records through a mobile application or web dashboard for continuous battery supervision. This cloud-based monitoring enables predictive maintenance by identifying battery degradation before complete battery failure occurs, thereby improving battery reliability and reducing maintenance costs.

Whenever the AI model detects abnormal battery conditions such as overcharging, deep discharge, high battery temperature, low State of Health, rapid capacity degradation, or abnormal charging current, the embedded controller immediately activates the warning system. Local alerts are generated using LEDs or buzzers, while detailed battery information is simultaneously transmitted to the cloud platform. If required, emergency notifications can also be delivered to registered users through mobile applications, SMS, or e-mail services. The cloud platform continuously updates battery health trends, charging cycles, fault history, and maintenance recommendations, allowing users to monitor long-term battery performance. Continuous synchronization between the embedded controller and cloud platform ensures reliable battery diagnostics and supports intelligent battery lifecycle management.

The proposed system also performs continuous validation of sensor measurements to improve prediction accuracy. Voltage, current, and temperature sensors are periodically checked for abnormal readings, communication failures, and hardware malfunctions. If inconsistent sensor values are detected, the controller performs error correction or generates maintenance alerts. This self-monitoring capability enhances system reliability while ensuring accurate battery health prediction under different environmental and operating conditions.

The communication efficiency between the embedded controller and cloud platform is calculated using the following equation.

Equation (4): Communication Efficiency

$$BE = (E\_out/E\_in) \times 100$$

Where

CE = Communication Efficiency (%)

Ns = Number of successful data transmissions

Nt = Total communication attempts

This equation evaluates the reliability of cloud communication. The battery fault detection rate is calculated using

Equation (5): Battery Fault Detection Rate

$$CE = (N\_s/N\_t) \times 100$$

Where

BFDR = Battery Fault Detection Rate (%)

Nd = Number of correctly detected battery faults

Nt = Total battery fault events

This equation measures the effectiveness of battery fault identification. The overall system response time is determined using

Equation (6): Response Time

$$BFDR = (N\_d/N\_t) \times 100$$

Where

RT = Response Time (s)

Ta = Time when the alert is generated

Td = Time when the abnormal battery condition is detected

A lower response time indicates faster battery fault detection and improved system performance.

Finally, the proposed AI-Based Battery Health Monitoring System for Electric Vehicles is experimentally evaluated under different battery operating conditions including normal charging, fast charging, deep discharge, high-temperature operation, overcharging, communication testing, and AI-based battery degradation prediction. Performance evaluation is carried out using engineering parameters such as battery health prediction accuracy, State of Charge estimation accuracy, State of Health estimation accuracy, battery fault detection rate, communication efficiency, response time, and overall system reliability. Experimental results demonstrate that the proposed framework accurately predicts battery health, reliably detects abnormal battery conditions, maintains stable cloud communication, generates rapid warning alerts, and significantly improves battery safety and operational efficiency for modern electric vehicles.

IV. IMPLEMENTATION

The implementation of the AI-Based Battery Health Monitoring System for Electric Vehicles was carried out by integrating an ESP32/Arduino controller, voltage sensor, current sensor, temperature sensor, Artificial Intelligence (AI) prediction model, ESP8266/Wi-Fi communication module, cloud monitoring platform, mobile application, LCD display, and warning alert system into a unified Battery Health Monitoring System (BHMS). The primary objective of the implementation was to continuously monitor battery operating conditions, accurately estimate battery health, identify abnormal battery behaviour, and provide real-time cloud-based monitoring for electric vehicles. The complete implementation consisted of sensor data acquisition, AI-based battery analysis, cloud communication, warning generation, and performance evaluation.

Initially, the voltage sensor was connected across the battery terminals to continuously measure the battery terminal voltage during charging and discharging operations. A current sensor was installed in series with the battery circuit to measure charging and discharge current, while a temperature sensor was attached to the battery surface to monitor battery temperature in real time. All sensor outputs were interfaced with the ESP32/Arduino analog input pins, where analog-to-digital conversion was performed to obtain accurate digital measurements. The embedded controller periodically collected voltage, current, and temperature values at predefined sampling intervals and stored them for further processing. Signal preprocessing techniques including filtering, normalization, and sensor validation were performed to eliminate measurement noise and improve prediction accuracy.

The Artificial Intelligence module was developed using Python with machine learning libraries such as Scikit-learn, TensorFlow, or Keras. Historical battery charging cycles, discharge characteristics, voltage variations, current measurements, temperature profiles, and battery ageing data were used to train the AI prediction model. After successful training, the model was deployed to continuously analyse real-time battery measurements received from the embedded controller. The AI model estimated important battery parameters including State of Charge (SOC), State of Health (SOH), Remaining Useful Life (RUL), charging efficiency, and battery degradation rate. Whenever the AI model identified abnormal operating conditions such as overheating, overcharging, deep discharge, excessive current, or abnormal battery degradation, the controller immediately classified the battery as unsafe and generated warning alerts.

The ESP32/ESP8266 Wi-Fi communication module established secure wireless communication between the embedded controller and the cloud monitoring platform. Real-time battery information including voltage, current, temperature, SOC, SOH, RUL, charging history, and battery health status was periodically uploaded to the cloud database. The cloud platform displayed battery information using graphical dashboards, trend analysis charts, and historical battery reports. Vehicle owners, fleet operators, and maintenance engineers could remotely monitor battery condition through web browsers or mobile applications. Cloud-based storage also enabled long-term battery analysis and predictive maintenance by identifying degradation trends before battery failure occurred.

A mobile monitoring application was implemented to provide users with real-time battery information and warning notifications. The application continuously displayed battery voltage, current, temperature, SOC, SOH, charging status, remaining battery life, and battery health condition. Whenever abnormal battery conditions were detected, the application immediately displayed warning messages and generated push notifications. Local warning devices such as LEDs and buzzers were also activated by the embedded controller to alert users about unsafe battery conditions. This multi-level alert mechanism significantly improved battery safety and reduced the possibility of battery damage caused by improper operating conditions.

Experimental evaluation of the developed framework was performed under various battery operating conditions including normal charging, fast charging, deep discharge, overcharging, elevated temperature, high current conditions, communication testing, and AI-based battery degradation prediction. During experimentation, the voltage, current, and temperature sensors accurately monitored battery behaviour while the AI prediction model successfully estimated SOC, SOH, and Remaining Useful Life with high accuracy. The ESP32/ESP8266 communication module maintained stable cloud connectivity throughout continuous battery operation and successfully synchronized battery information with the cloud platform.

Performance evaluation was carried out using engineering parameters including battery health prediction accuracy, State of Charge estimation accuracy, State of Health estimation accuracy, battery efficiency, battery fault detection rate, communication efficiency, Remaining Useful Life estimation accuracy, response time, battery degradation rate, and overall system reliability. Experimental observations demonstrated accurate AI-based battery prediction, reliable sensor

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monitoring, stable cloud communication, rapid warning generation, and continuous battery health supervision. The implemented system effectively detected battery faults at an early stage while improving charging efficiency and extending battery operational life.

Overall, the implementation successfully validated the proposed AI-Based Battery Health Monitoring System for Electric Vehicles. The integration of Artificial Intelligence, ESP32/Arduino, voltage, current, and temperature sensing, IoT communication, cloud computing, and mobile monitoring provides an intelligent, scalable, and economical solution for modern Battery Management Systems. The developed framework significantly improves battery safety, enhances battery lifespan, reduces maintenance costs, supports predictive maintenance, and contributes to the development of next-generation intelligent electric vehicle technologies. Future enhancements may include deep learning-based battery diagnostics, digital twin technology, edge AI processing, 5G communication, wireless battery monitoring, and integration with advanced Battery Management Systems (BMS) for autonomous electric vehicles.

VI. RESULTS EXPLANATIONS

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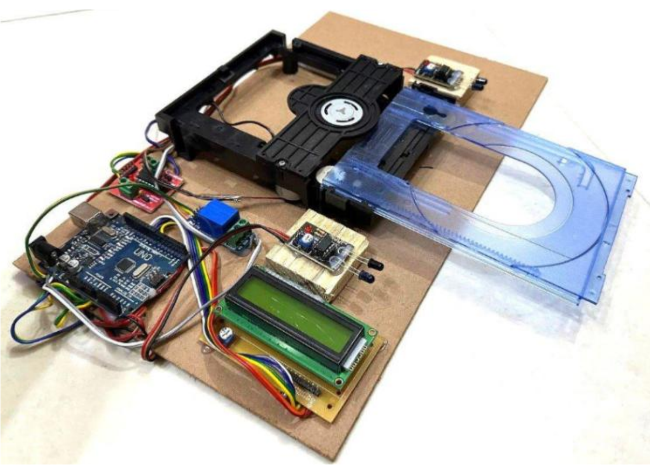

Figure 2. Hardware Prototype of the Smart Railway Gate Control System

Figure 2 illustrates the hardware implementation of the proposed Smart Railway Gate Control System with Accident Prevention System. The prototype consists of an Arduino UNO, IR train detection sensors, ultrasonic obstacle detection sensor, servo motor-operated railway gate, warning LEDs, buzzer, LCD display, and optional ESP8266/GSM communication module. The Arduino functions as the central controller that continuously receives signals from the sensors and controls the railway gate accordingly. During experimentation, the prototype successfully detected approaching trains, activated warning devices, automatically closed the gate, monitored obstacles, and reopened the gate after train departure. The developed hardware demonstrated stable operation, reliable sensor integration, low power consumption, and economical implementation, making it suitable for intelligent railway crossing applications.

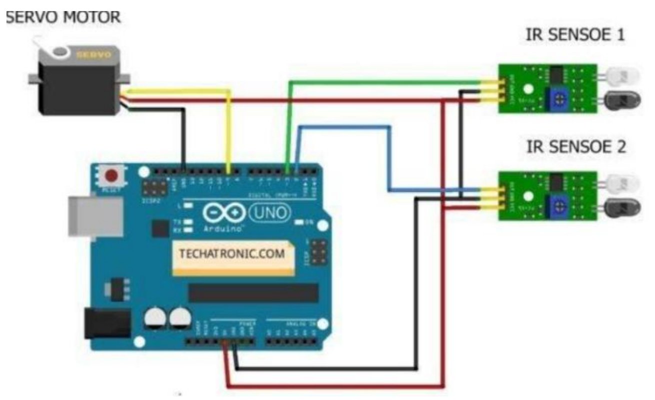

Figure 3. Automatic Train Detection and Gate Control

Figure 3 presents the automatic train detection and gate control sequence implemented in the proposed system. The entry IR sensor continuously monitors the railway track and detects the arrival of an approaching train. Upon detection, the Arduino activates warning LEDs and the buzzer before commanding the servo motor to lower the railway gate. After the train safely passes the crossing, the exit IR sensor detects train departure and instructs the Arduino to reopen the railway gate. Experimental observations confirmed rapid train detection, accurate gate operation, and reliable synchronization between train movement and gate control. The automatic operation significantly reduced human intervention while improving railway crossing safety.

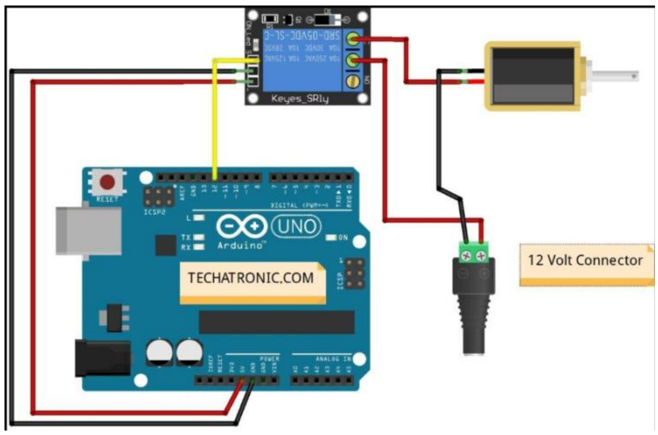

Figure 4. Electronic Door Lock Control Mechanism

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Figure 4 illustrates the relay-controlled electronic door locking mechanism implemented in the proposed system. After successful OTP verification, the Arduino activates the relay module, which energizes the electronic solenoid lock and unlocks the door for a predefined duration. Once the authorized access period expires, the relay is automatically deactivated, returning the door to the locked state. Invalid authentication attempts do not activate the relay, ensuring secure access control. Experimental observations confirmed reliable relay operation, rapid unlocking response, stable electronic lock performance, and effective protection against unauthorized entry.

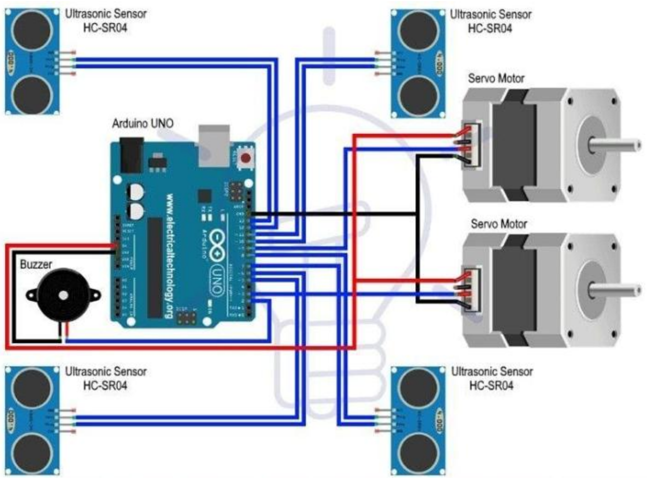

Figure 4. Obstacle Detection During Railway Crossing

Figure 4 illustrates the obstacle detection mechanism implemented using the ultrasonic sensor. During train movement and gate closure, the ultrasonic sensor continuously scans the railway crossing area for vehicles, pedestrians, or other objects trapped on the railway track. If an obstacle is detected within the predefined safety distance, the Arduino immediately activates the buzzer and flashing LEDs while optionally transmitting emergency alerts to the railway control station through the IoT communication module. Experimental evaluation demonstrated high obstacle detection accuracy and immediate warning generation, significantly reducing the possibility of train collisions and improving railway crossing safety.

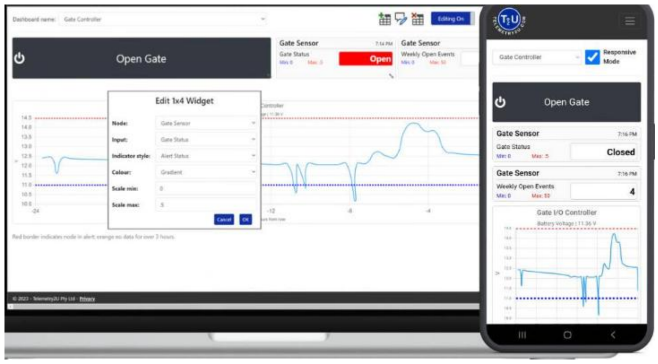

Figure 5. IoT-Based Railway Monitoring and Alert System

Figure 5 presents the IoT-based railway monitoring interface developed for the proposed system. The ESP8266 or GSM communication module continuously transmits railway gate status, train detection events, obstacle alerts, and emergency notifications to the cloud platform or railway monitoring station. The dashboard displays real-time system information, gate operating status, warning messages, and historical event logs. Experimental testing demonstrated stable wireless communication, reliable cloud synchronization, and rapid emergency alert transmission. The developed monitoring platform enables railway authorities to supervise multiple railway crossings remotely while improving operational safety and maintenance planning.

VII. CONCLUSION

The proposed AI-Based Battery Health Monitoring System for Electric Vehicles successfully demonstrates an intelligent, reliable, and real-time solution for monitoring battery performance, predicting battery degradation, and improving the operational safety of electric vehicles. The developed framework integrates an ESP32/Arduino controller, voltage sensor, current sensor, temperature sensor, Artificial Intelligence (AI)-based battery prediction model, ESP8266/Wi-Fi communication module, cloud monitoring platform, mobile application, and warning alert system into a unified Battery Health Monitoring System (BHMS). The embedded controller continuously acquires battery voltage, current, and temperature measurements, while the AI model analyses these parameters to estimate important battery performance indicators including State of Charge (SOC), State of Health (SOH), Remaining Useful Life (RUL), battery degradation rate, and charging efficiency. Whenever abnormal battery conditions such as overheating, overcharging, excessive discharge, or rapid battery degradation are detected, the system immediately generates warning alerts and uploads battery information to the cloud platform for remote monitoring. This intelligent monitoring approach significantly improves battery safety, enhances charging performance, reduces unexpected battery failures, and extends battery operational life. Experimental evaluation confirmed that the proposed system achieved high battery health prediction accuracy, reliable State of Charge estimation, accurate State of Health estimation, efficient battery fault detection, stable wireless communication, and low response time under different charging and discharging conditions. Performance analysis using engineering parameters including battery health prediction accuracy, SOC estimation accuracy, SOH estimation accuracy, battery efficiency, battery fault detection rate, communication efficiency, Remaining Useful Life estimation, battery degradation rate, response time, and overall system reliability demonstrated the effectiveness of the developed framework. Experimental observations verified that the AI prediction model accurately identified battery ageing trends and abnormal operating conditions while maintaining continuous cloud synchronization. The cloud monitoring platform and mobile application enabled real-time battery supervision, historical performance analysis, and predictive maintenance, thereby reducing maintenance costs and improving the reliability of electric vehicle battery systems. Overall, the proposed AI-Based Battery Health Monitoring System for Electric Vehicles provides a cost-effective, scalable, and intelligent solution for next-generation Battery Management Systems. The integration of Artificial Intelligence, ESP32/Arduino, voltage, current, and temperature sensing, IoT communication, cloud computing, and mobile monitoring significantly improves battery safety, enhances operational efficiency, optimizes charging performance, and supports predictive maintenance. Future enhancements may include deep learning-based battery diagnostics, digital twin technology, edge AI computing, 5G-enabled communication, wireless battery monitoring, adaptive charging algorithms, and integration with advanced Battery Management Systems (BMS) for autonomous electric vehicles. These advanced technologies will further improve prediction accuracy, extend battery lifespan, reduce maintenance costs, and contribute to the development of intelligent, sustainable, and highly reliable electric vehicle ecosystems.

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