Intelligent Digital Twins for Battery Management with Explainable AI

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Abstract- **This project proposes a novel approach in the battery state prediction of electric vehicles using Explainable Data-Driven Digital Twins with advanced machine learning algorithms such as deep Neural Networks (DNN), Long Short-Term Memory (LSTM) networks, Convolutional Neural Networks (CNN), Support Vector Regression (SVR), Support Vector Machines (SVM), Feedforward Neural Networks (FNN), Radial Basis Function networks (RBF), Random Forests (RF), and Extreme Gradient Boosting (XGBoost). Therefore, the aim would be to better predict important parameters of the battery, such as SOC and SOH, by running these under different operation conditions. These are achieved in the digital twin model by means of a diversification of a set of algorithms to achieve very high accuracy as well as robustness, followed by the employment of XAI techniques to better explain the predicted values. Preliminary results suggest that this integrated approach significantly outperforms traditional methods in terms of accuracy and reliability and significantly contributes to the advancement of intelligent, adaptive battery management systems crucial for future electric mobility.**

Keywords: **Electric vehicles, battery prediction, Digital Twins, machine learning, DNN, LSTM, XGBoost, SOC, SOH, Explainable AI, adaptive battery management.**

I. INTRODUCTION

The shift towards electric vehicles has brought with it new challenges in battery management, where accurate prediction of battery states is critical for optimal performance, safety, and longevity. As the demand for EVs grows, the need for robust and reliable BMS becomes more critical. Traditional methods do not provide the accuracy and flexibility to be used in modern applications of EVs. These methods sometimes estimate wrong state-of-charge and state-of-health parameters, due to which their performance and lifecycle may get deteriorated. This project aims at developing an SOC and SOH prediction method that utilizes a digital twin paired with explainable data-driven approaches. The usage of advanced algorithms like DNN, LSTM networks, CNN, and many more for the modeling purpose, through which complexities in battery behavior are captured to yield the most accurate predictions and also through the use of explainable AI techniques such as SHAP and LIME increase transparency and trustworthiness within the model that would support good decisions and durable battery life.

A. Problem Statement.

The increasing adoption of electric vehicles has placed significant demand on the accurate prediction of battery states, particularly SOC and SOH. Traditional prediction methods struggle with the complexity and dynamic nature of battery systems, leading to suboptimal battery management and reduced performance. Inaccurate predictions can cause shorter battery lifespan, unexpected failures, and inefficient energy utilization, ultimately affecting the reliability and acceptance of EVs. Moreover, most machine learning models lack interpretability, and therefore, it is very hard to figure out the causes of factors influencing battery states. This project aims to overcome challenges with an overall comprehensive digital twin model that can predict battery states precisely and provide insight about the underlying factors affecting performance, thereby enhancing the efficiency and reliability and safety in EVs.

B. Existing System

Existing EV battery state forecasting systems are based on conventional models such as linear regression and rule-based algorithms, which are imprecise and inflexible with oversimplified assumptions. These systems are also not interpretable, and users are unable to grasp factors affecting performance or diagnose problems. Recent machine learning methods such as ANN, ELM, LSTM, and DCNN have enhanced SOH estimation but still suffer from a lack of transparency and predictability. Hence, sophisticated, interpretable, and data-driven solutions are needed.

II. PROPOSED SYSTEM

The proposed system improves battery state prediction in electric vehicles through the use of Explainable Data-Driven Digital Twins. It will combine a set of the latest advanced machine learning algorithms: Deep Neural Networks (DNN), Long Short-Term Memory (LSTM) networks, Convolutional Neural Networks (CNN), Support Vector Regression (SVR), Support Vector Machines (SVM), Feedforward Neural Networks (FNN), Radial Basis Function (RBF), Random Forests (RF), and Extreme Gradient Boosting (XGBoost). This algorithm combination aims to achieve highly accurate and reliable prediction of battery parameters related to SOC and SOH. The inclusion of explainable AI techniques in this design ensures the transparency of its predictions, therefore gaining trust and highlighting the factors that impact battery performance. Such a system enhances prediction accuracy, adaptability, and interpretability far beyond the current systems.

III. LITERATURE SURVEY

Accurate estimation of the battery state-of-health and state-of-charge are very critical in order to ensure that electric vehicle batteries will operate as desired. Various data-driven algorithms and models have been proposed for addressing such challenges. A recent approach makes use of a neural network that uses partial data such as voltage, current, and temperature in order to estimate SOH within a narrow range of state-of-charge. This method depicts great accuracy: an RMSE less than 0.9% for numerous datasets, illustrating that it may be reliable and accurate enough to apply to reality [1].

Several other BMS technologies, with electric, thermal, or electro-thermal models, monitor and optimize hybrid and electric vehicle battery performance. These models facilitate estimation of battery states in charging protocols for better management of the device. In this paper, the optimization of the BMS tasks on temperature management and protection of the battery is stressed and gaps seen in previous research that will pull their wagon in bringing innovative developments in the estimation of battery states [2].

While much research on BMS has been focused on EVs, there is a growing need for research specific to unmanned aerial vehicles (UAVs). UAV BMS are essential for managing charging, discharging, state estimation, and fault diagnosis, especially given the rapid advancements in battery technologies and big data. Research in this field identified some challenges and room for improvement that might be brought in the estimation of battery SOC, SOH, and remaining useful life as well as the system safety and fault diagnosis. UAV BMS is thus seen as a promising candidate for future study [3].

Other studies have also addressed fast and real-time methods for the computation of SOH and SOC. One method utilizing partial discharge intervals and comparing open-circuit voltage (OCV) curves with reference models proved to predict SOH and SOC with accuracy. For validation, this method proved correct with a NASA dataset with SOH and SOC errors less than 1%. Predictions improved again when updating the OCV curve with temperature data. This suggests that these online methods hold significant promise for the monitoring of real-time battery packs and prediction capabilities [4].

Moreover, digital twin frameworks have been explored for EV battery management, integrating AI technologies such as extreme gradient boosting (XGBoost) and the extended Kalman filter (EKF) to enhance SOC and SOH predictions. These frameworks continuously update models to account for aging effects and capacity degradation, thus improving situational awareness and allowing real-time adjustments to optimize battery performance and extend lifespan [5].

A comprehensive survey on data-driven methods for SOH estimation summarizes various techniques used in battery state estimation, which indicate the challenges brought about by the complex electrochemical processes and different working conditions. The review compares and contrasts different data-driven methods that have been discussed for their advantages and disadvantages in real-world EV applications. This critical analysis intends to provide practical knowledge regarding the field and direct future improvements of SOH estimation techniques for more reliable and accurate battery management [6].

IV. SYSTEM DESIGN

A. Design

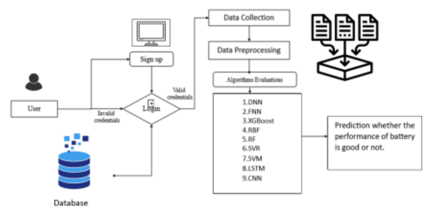

Figure1: System Design

The figure illustrates an AI-assisted digital twin-based EV battery state prediction and management system. User registration or login is performed, with passwords verified against a secure database. Collected data is preprocessed to allow advanced analysis with machine learning algorithms like DNN, FNN, XGBoost, RBF, RF, SVR, SVM, LSTM, and CNN. The system focuses on critical battery parameters—SOC and SOH—to improve reliability, safety, and lifespan. Explainable AI (XAI) techniques enhance explainability so that stakeholders can understand predictions. The technique enhances accuracy significantly over traditional techniques, enabling intelligent and adaptive battery management for green electric mobility.

V. ALGORITHMS

1. DNN, CNN, LSTM
2. Support Vector Regression (SVR) and Support Vector Machines (SVM)
3. Feedforward Neural Networks (FNN) and Radial Basis Function (RBF)
4. Random Forest (RF)

5. Extreme Gradient Boosting (XGBoost)

VII. CONCLUSION

This paradigm utilizes XAI-driven Data-Driven Digital Twins to improve the reliability and accuracy of EV battery state forecasts, such as SOC and SOH. By combining sophisticated machine learning algorithms with XAI methods such as SHAP and LIME, it achieves both high predictive accuracy and explainability. Proactive battery control is made possible, optimizing charging modes and operating conditions to enhance efficiency and lifespan. Finally, it facilitates the creation of more reliable and eco-friendly electric vehicles.

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