Predicting the health of Lithium ion Batteries using Machine Learning.

Aayush Swami , Computer Science

Mentor: Nicholas Rolston

School of Electrical, Computer & Energy Engineering

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Objective & Research Question:

Can machine learning models, specifically Gaussian Process Regression (GPR), accurately predict lithium-ion battery health using Electrochemical Impedance Spectroscopy (EIS) data to improve efficiency and lifespan?

Background:

- Lithium-ion batteries are widely used in electronics, electric vehicles, and grid storage.
- Battery degradation over time affects performance and safety.
- Traditional health diagnostics like capacity fade tests are expensive and time-consuming.
- Machine learning offers a data-driven, scalable alternative for battery health monitoring.
- GPR is ideal for modeling complex, non-linear degradation patterns.

What is EIS?

Electrochemical Impedance Spectroscopy (EIS) is a diagnostic technique that applies small alternating current (AC) signals at varying frequencies to a battery and measures its response. It reveals electrochemical properties like resistance and capacitance — giving insight into battery health without requiring full charge-discharge cycles.

This project uses real EIS data collected from commercial-grade lithium-ion batteries undergoing realistic usage and degradation.

Methods:

- Data Source: EIS data from commercial batteries at different charge-discharge cycles.
- Preprocessing: Filtered frequencies (0.2–20,000 Hz), dropped null values and cycle 0.
- Feature Engineering: Real and imaginary impedance (Re(Z), Im(Z)) paired at each frequency as model features.
- Model: Gaussian Process Regressor (with RBF kernel) trained on standardized impedance features.
- Comparison: GPR model based on EIS vs. a cycle-based GPR baseline.

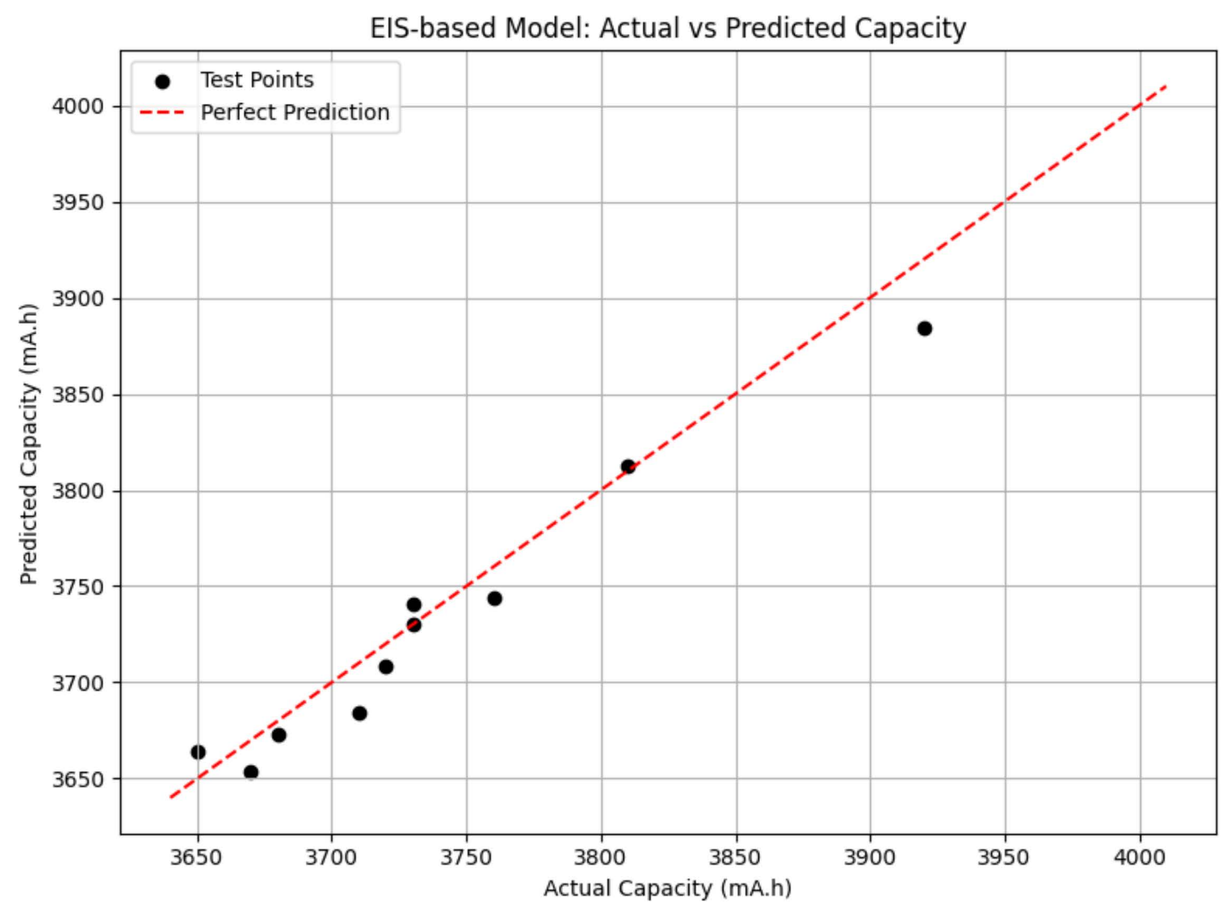

Fig 1: EIS-based GPR — Actual vs Predicted Capacity
Description: Compares predicted vs actual battery capacity.
Explanation: Strong alignment with the diagonal line shows high model accuracy.

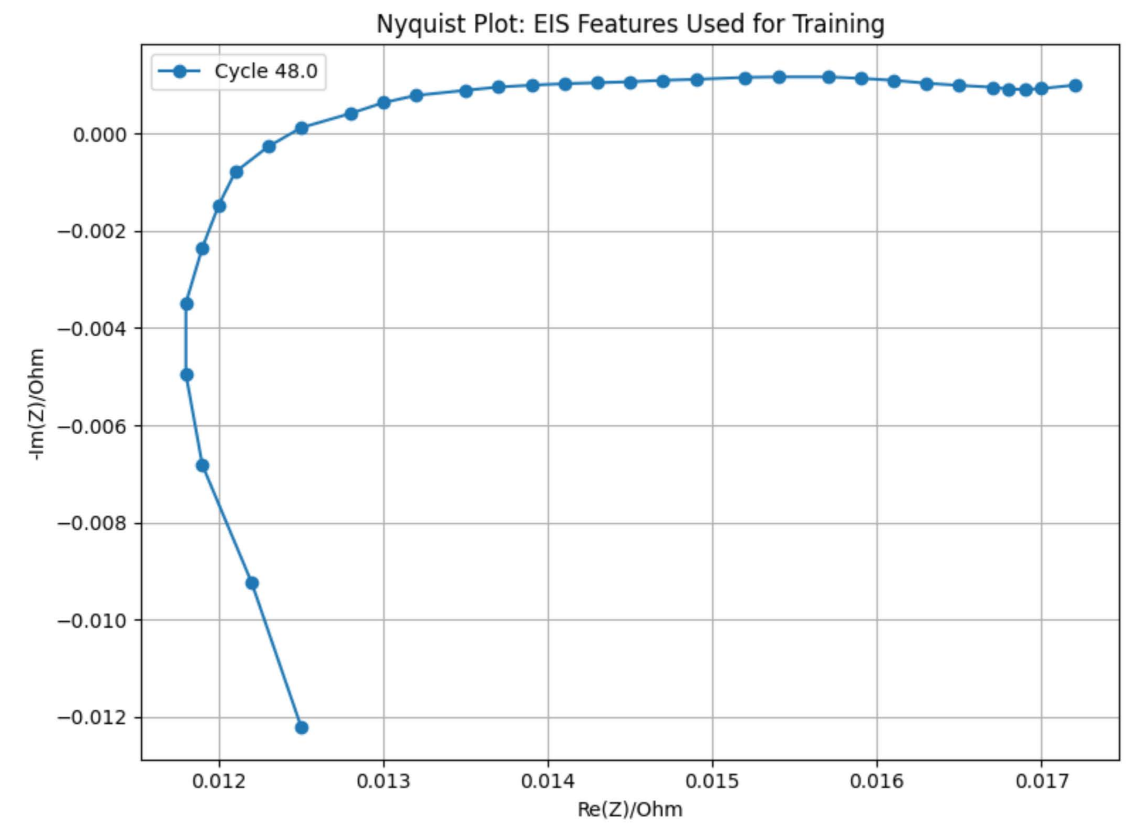

Fig 2: Nyquist Plot of Impedance Evolution Across Cycles
Description: Shows how impedance changes as the battery ages.
Explanation: Curve shape shifts with cycles, revealing degradation patterns used as model features.

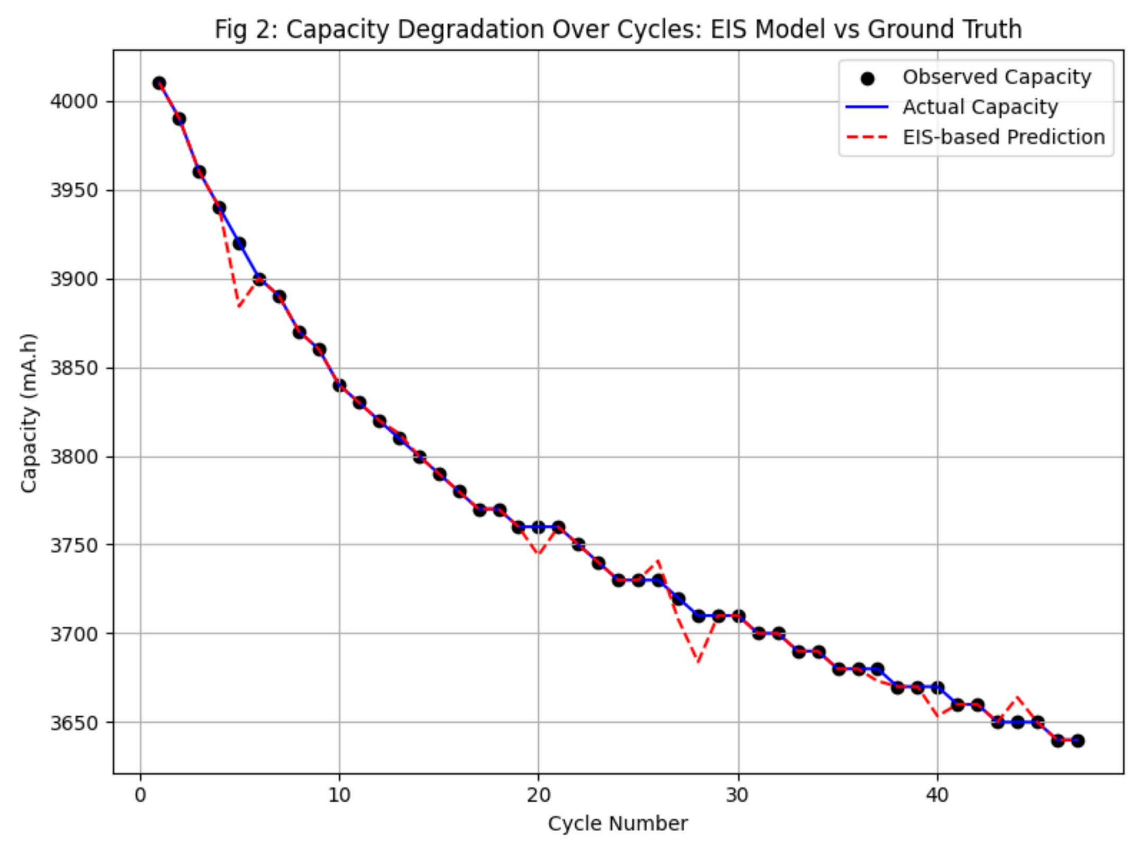

Fig 3: Capacity Degradation Over Cycles — EIS Model vs Ground Truth
Description: Plots model predictions vs actual capacity across cycles.
Explanation: EIS model closely follows real degradation, proving it can track battery aging.

Results & Discussion:

- The EIS-based GPR model achieved a high R^2 of 0.946 and low RMSE of 17.36 mAh, indicating strong predictive accuracy.
- The model was trained on real and imaginary impedance across 69 frequencies (138 features total).
- Nyquist plots showed clear impedance evolution over cycles, which the model used to estimate capacity.
- Data was collected from lithium-ion batteries under realistic usage conditions.
- This method provides a non-invasive, scalable solution for accurate battery health monitorin

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Ira A. Fulton Schools of Engineering
Arizona State University