Real-Time Intelligent Control System to Address Faults for DC Motors

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Abstract

This project focuses on enhancing the modeling of Permanent Magnet DC (PMDC) motors through the application of advanced machine learning techniques. The primary objective is to develop accurate predictive models for key motor parameters, which are essential for efficient motor control and performance optimization.

Initially, we developed models to predict motor velocity based on voltage inputs. This involved training machine learning algorithms on a dataset comprising various voltage inputs and their corresponding motor velocities. Additionally, we created models to estimate rotor angular velocity from pulse width modulation (PWM) signals. These models were trained using data that mapped PWM signals to the resulting angular velocities of the rotor.

The predictive models for motor velocity and rotor angular velocity were then Integrated to estimate rotor temperature. Rotor temperature is a critical parameter that significantly affects motor efficiency and longevity, yet it is challenging to measure directly due to the nonlinear behavior of PMDC motors. By combining the outputs of the velocity and angular velocity models, we developed a comprehensive approach to estimate rotor temperature accurately.

Our approach aims to improve motor control and efficiency in practical applications by providing more accurate predictions of these key parameters. This enhanced modeling can lead to better performance, reduced energy consumption, and extended lifespan of PMDC motors. Future work will focus on applying these models to actively control rotor temperature, further improving motor performance and longevity. This project demonstrates the potential of machine learning to overcome the limitations of traditional methods, offering significant advancements in the field of motor control and efficiency.

Table of Contents

Introduction ***4***

Challenges ***5***

Methodology ***8***

Results ***10***

- ***Model 1*** ***10***
- ***Model 2*** ***11***
- ***Model 3*** ***13***

Conclusion ***14***

References ***15***

Introduction

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This enhanced modeling can lead to better performance, reduced energy consumption, and extended lifespan of PMDC motors. Future work will focus on applying these models to actively control rotor temperature, further improving motor performance and longevity. This project demonstrates the potential of machine learning to overcome the limitations of traditional methods, offering significant advancements in the field of motor control and efficiency.

Challenges

Accurately predicting key parameters of Permanent Magnet DC (PMDC) motors, such as motor velocity, rotor angular velocity, and rotor temperature, presents significant challenges due to the inherent nonlinear behavior of these systems. PMDC motors exhibit complex dynamics that are influenced by various factors, including electrical inputs, mechanical properties, and thermal effects. Traditional modeling methods, which often rely on linear approximations or simplified assumptions, struggle to capture these intricate relationships, leading to suboptimal predictions and control strategies.

One of the most critical parameters to estimate is rotor temperature. Rotor temperature directly impacts motor efficiency, performance, and longevity. High temperatures can lead to increased resistance, reduced magnetic properties, and potential damage to motor components. However, measuring rotor temperature directly is difficult due to the rotating nature of the rotor and the harsh operating environment. Traditional methods, such as using thermocouples or infrared sensors, are either impractical or provide limited accuracy.

To illustrate these challenges, **Figure 1** shows the nonlinear relationship between velocity and pulse-width modulation (PWM), highlighting the limitations of traditional linear models. **Figure 2** depicts the relationship between velocity and motor voltage, emphasizing the need for advanced modeling techniques to capture the initial steep increase and subsequent plateau in motor voltage as velocity increases. **Figure 3** demonstrates the nonlinear behavior of motor speed and temperature, showing that temperature remains relatively stable at lower

speeds but increases sharply at higher speeds, indicating the complexity of predicting temperature based on velocity.
This project addresses these challenges by leveraging machine learning techniques to develop predictive models that can accurately estimate motor velocity, rotor angular velocity, and rotor temperature. By training machine learning algorithms on extensive datasets that capture the complex interactions within PMDC motors, we aim to create models that can generalize well to various operating conditions. These models are designed to improve the accuracy of parameter predictions, thereby enhancing motor control and performance in practical applications.

The Integration of machine learning models allows for a more comprehensive understanding of the motor's behavior, enabling better control strategies that can adapt to changing conditions. This approach not only improves the immediate performance of the motor but also contributes to its long-term reliability and efficiency. By addressing the limitations of traditional methods, our project aims to provide a robust solution for the accurate prediction and control of key parameters in PMDC motors, ultimately leading to more efficient and reliable motor systems.

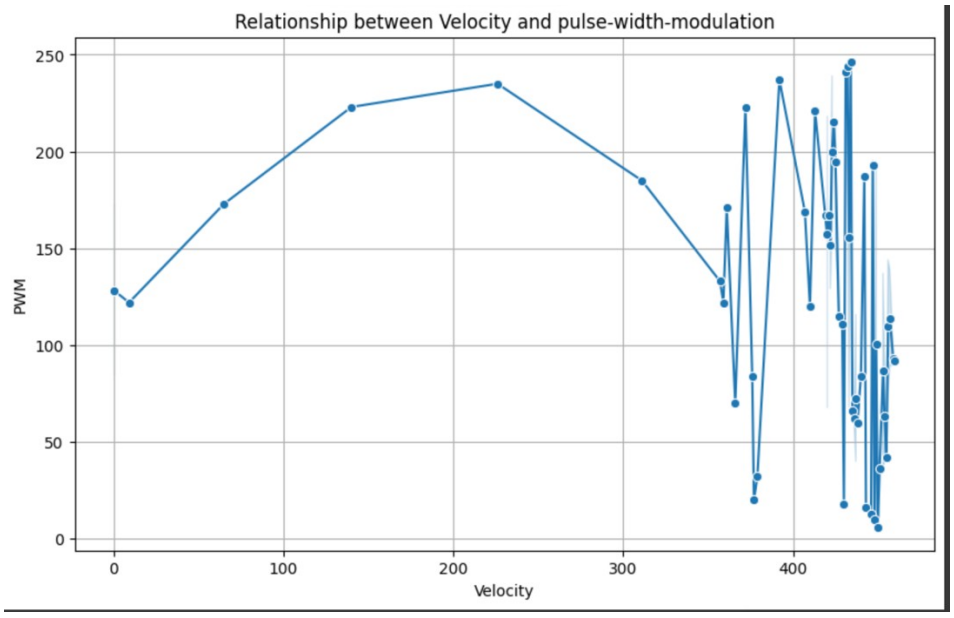


Figure 1 *shows the non-linear relationship between Velocity and PWM.*

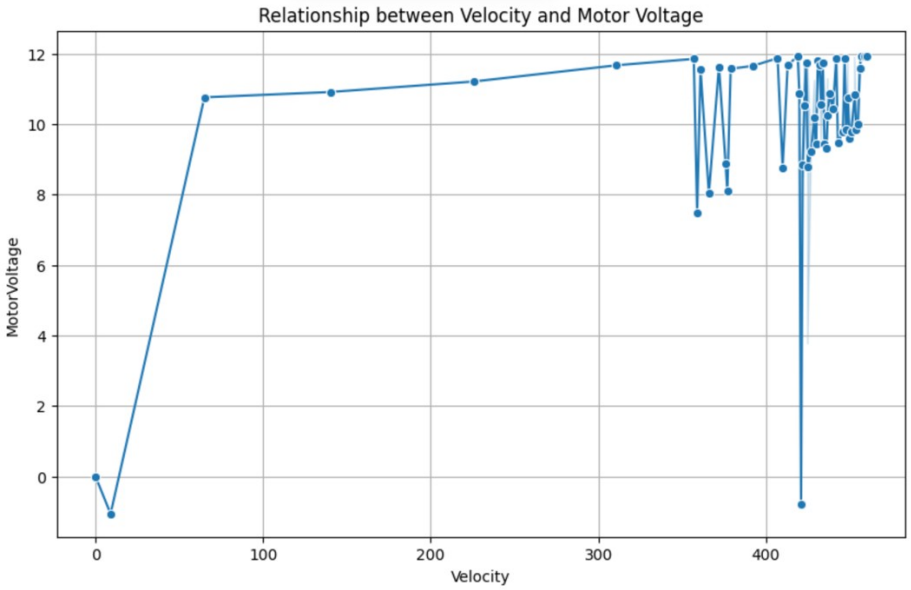


Figure 2: *Velocity vs. Motor Voltage (Non-linear relationship requiring advanced modeling)*

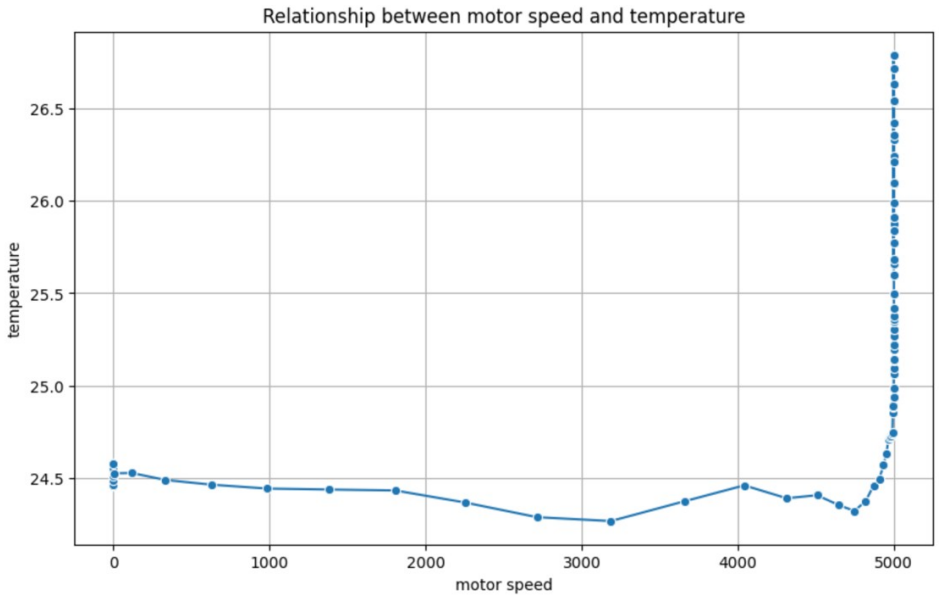


Figure 3: *Motor Speed vs. Temperature (Non-linear relationship, temperature increases sharply at higher speeds)*

Methodology

Our methodology involves a comprehensive process of collecting and preprocessing sensor data from the Permanent Magnet DC (PMDC) motor to develop predictive models for key motor parameters. The first step is to gather data from various sensors attached to the motor, which measure inputs such as voltage, current, and pulse width modulation (PWM) signals, as well as outputs like motor velocity and rotor angular velocity. This raw data is then preprocessed to remove noise, handle missing values, and normalize the data to ensure consistency and accuracy.

Once the data is preprocessed, we proceed to develop three distinct machine learning models. **Model 1** is designed to predict motor velocity based on the voltage inputs. This model is trained using a dataset that maps different voltage levels to their corresponding motor velocities, capturing the nonlinear relationship between these variables. **Model 2** focuses on estimating rotor angular velocity from PWM signals. By training this model on data that correlates PWM inputs with rotor angular velocities, we can accurately predict the rotor's speed under various operating conditions.

The outputs of Model 1 and Model 2 are then integrated into **Model 3**, which is tasked with estimating rotor temperature. Rotor temperature is a critical parameter that affects motor efficiency and longevity, but it is challenging to measure directly. By combining the predictions of motor velocity and rotor angular velocity, Model 3 can infer the rotor temperature with high accuracy. This model is trained on a dataset that includes temperature measurements alongside the predicted velocities and angular velocities, allowing it to learn the complex interactions between these variables.

To ensure the reliability and robustness of our models, we employ rigorous training and validation procedures. The models are trained using a portion of the dataset and validated on a separate subset to evaluate their performance. We use various machine learning algorithms, such as regression techniques, neural networks, and ensemble methods, to identify the best-performing models for each parameter.

Once the models are trained and validated, they are integrated into a real-time motor control system. This system continuously collects sensor data, processes it through the predictive models, and adjusts the motor's operation based on the predicted parameters. By providing accurate real-time predictions of motor velocity, rotor angular velocity, and rotor temperature, our approach enhances motor control, efficiency, and reliability. This integration allows for adaptive control strategies that can respond to changing conditions, ultimately leading to improved performance and extended lifespan of the PMDC motor.

To illustrate this methodology, **Figure 4** provides a diagram that outlines the entire process, from data collection and preprocessing to model training, validation, and real-time integration.

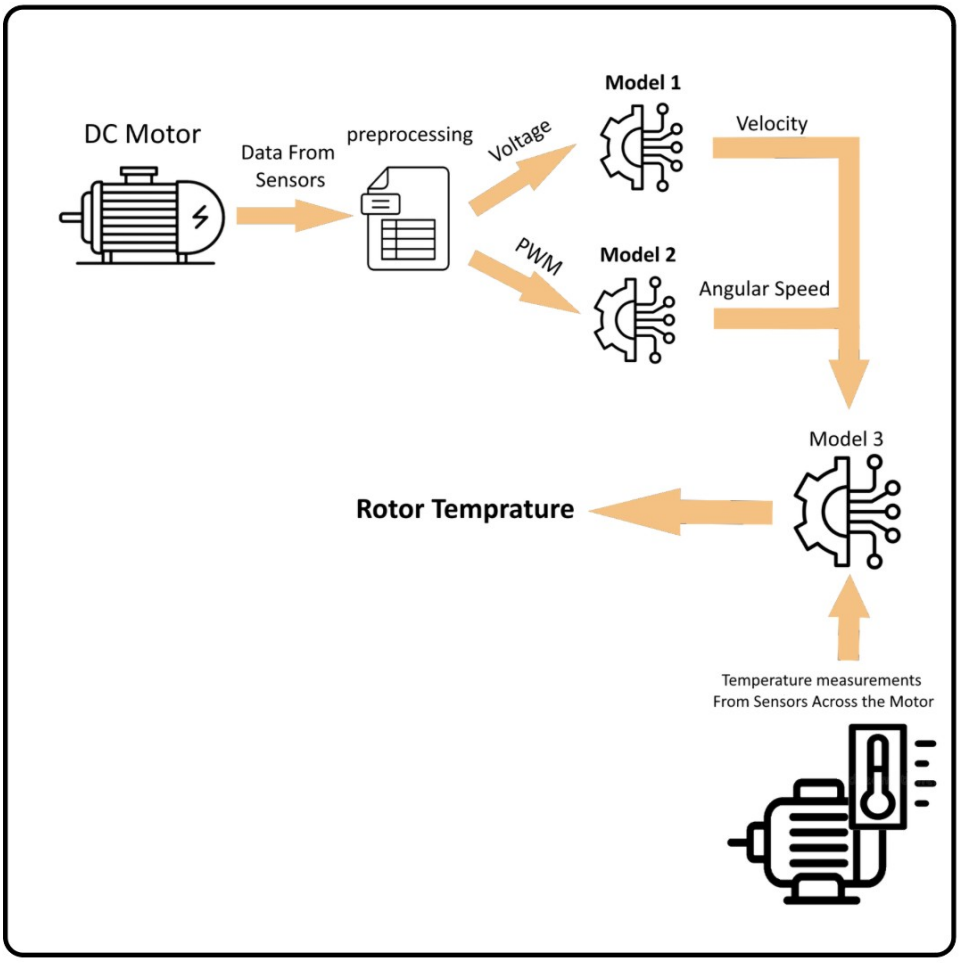


Figure 4: *Methodology Overview: Data Collection, Preprocessing, Model Training, Validation, and Real-Time Integration for PMDC Motor Parameter Prediction.*

Results

Model 1 Performance Metrics

The deep neural network model was evaluated using standard regression metrics, including the the R-squared (R^2) score, Mean Squared Error (MSE), and Mean Absolute Error. Table 1 summarizes these performance metrics for model 1 across the test dataset.

Model 1			
Model / Metric	R^2	Mean Squared	Mean Absolute

		Error	Error
Deep Neural Network	0.9114	3463.83	28.06

Table 1: *performance metrics for model 1 on the test dataset*

The model achieved a Mean Squared Error of 3463.83 and an R-squared value of 0.9114 suggests that the model explains 91.14% of the variance in the velocity data, demonstrating a strong fit to the observed data. The Mean Absolute Error (MAE) of the model's velocity predictions is 28.06. Given that the actual velocity in the dataset ranges from 0 to 400, this error represents approximately 7% of the maximum velocity. This indicates that the model's predictions are reasonably accurate, with most errors falling within a small fraction of the total velocity range.

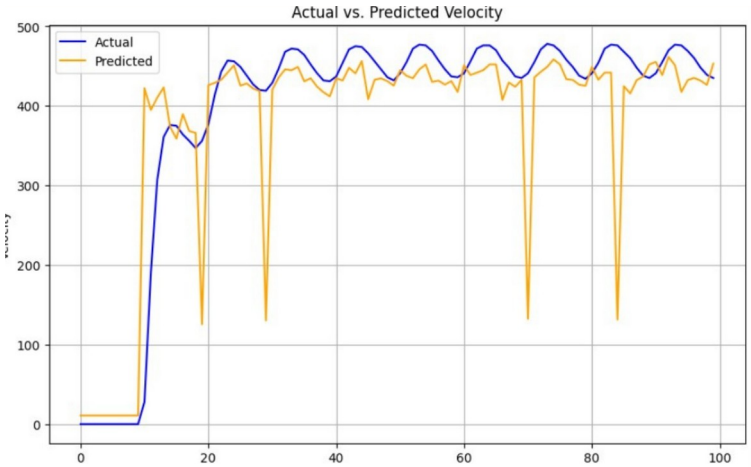


Figure 5: *actual motor velocity (Blue) vs predicted velocity (yellow)*

Temporal Comparison of Actual and Predicted Velocities

To further assess the model's predictive capability over time, the actual motor velocities were plotted against the predicted velocities. Figure 5 presents this comparison, with time on the x-axis and velocity on the y-axis.

Figure 5: Temporal Comparison of Actual and Predicted Motor Velocity

The graph illustrates that the predicted velocity (yellow line) closely aligns with the actual velocity (blue line) throughout the observed time period. The model successfully captures the dynamics of the motor's velocity, with most predictions closely matching the actual data points, though, there are spikes in the prediction where the model's prediction and the ground truth are quite different. This spiky behavior displayed in the graph is caused by voltage spikes in the dataset. Overall, minor deviations can be observed, but these discrepancies are relatively small and fall within 10 percent of the actual value.

Model 2 performance metrics

To predict angular velocity based on pulse width modulation (PWM), we evaluated the performance of multiple machine learning algorithms. Table 2 summarizes the performance metrics for all models tested across the test dataset.

Model 2			
Model / Metric	R^2	Mean Squared Error	Mean Absolute Error
OLS (Linear Regression)	1.0	1.58e-24	1.18e-12
Lasso	0.9999	1.43e-7	2.27e-4
Ridge	0.9999	4.39e-9	3.99e-5
Decision Tree	0.9999	4.37e-13	1.89e-8
Random Forest	0.9999	2.01e-4	1.75e-3
SVR	0.9875	55.87	2.84
K-Nearest Neighbors	0.9999	1.48e-3	5.28e-3
Gradient Boosting	0.9999	4.02e-2	0.100

Table 2: performance metrics for multiple machine learning models on the test dataset (predicting angular velocity using pulse width modulation as input)

The OLS Linear Regression model demonstrated superior performance with the highest R-squared value and the lowest MSE and MAE, indicating its efficacy in capturing the complex relationship between PWM and angular velocity.

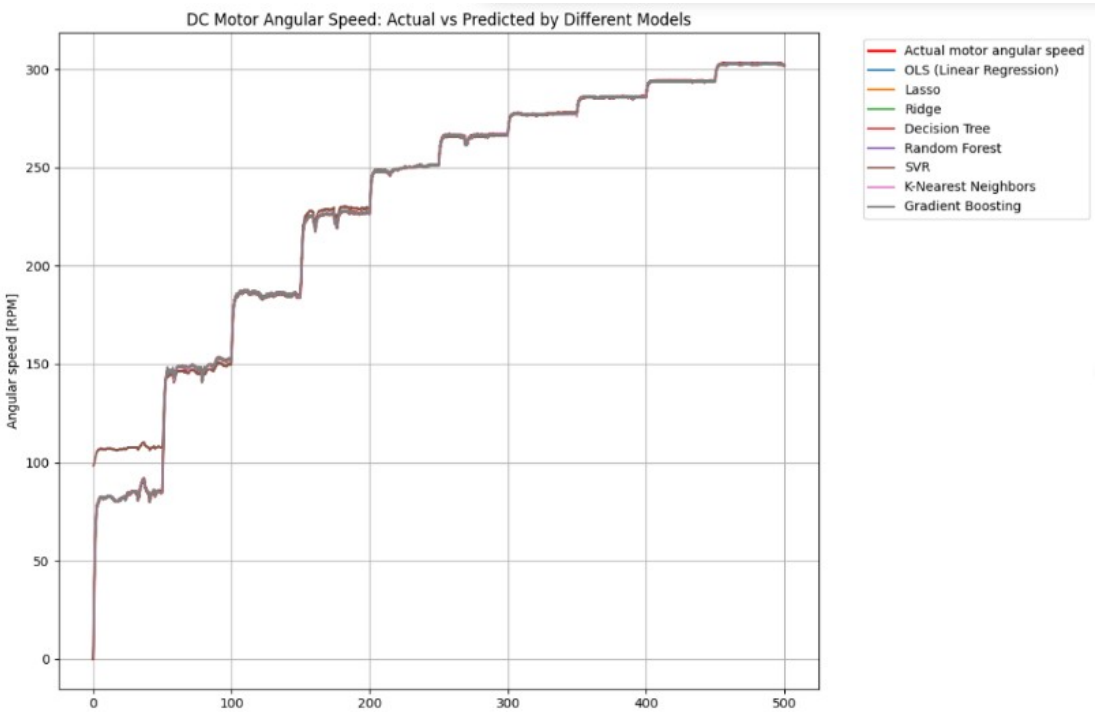


Figure 6: *actual angular velocity vs predicted angular velocity*

The accompanying graph illustrates the actual angular velocity versus the predicted angular velocities generated by the models over time. The x-axis represents time, while the y-axis denotes angular velocity. Each line, differentiated by color, corresponds to the predictions from a specific model. While all models displayed excellent performance, OLS Linear Regression (in blue) showed nearly perfect performance.

Model 3 Performance Metrics

To evaluate the performance of the models in predicting the rotor temperature of a DC motor, we compared the 1D Convolutional Neural Network (1D CNN) developed by Pranay Modukuru[1] with the Long Short-Term Memory (LSTM) network and the Bidirectional LSTM (Bi-LSTM) network we implemented. The models were assessed using three key metrics: R-squared (R^2) score, Mean Squared Error (MSE), and Mean Absolute Error (MAE).

Model 3			
Model / Metric	R^2	Mean Squared Error	Mean Absolute Error
1D CNN	0.9992	3.47e-5	4.15e-3
LSTM	0.9993	2.83e-5	3.93e-3
Bidirectional LSTM	0.9994	2.51e-5	3.79e-3

Table 3: performance metrics for temperature prediction models on the test dataset

Both the LSTM and Bi-LSTM models outperformed the 1D CNN in predicting the rotor temperature, yielding a slightly higher R-squared score as well as lower mean squared error, with the bi-directional LSTM model providing the best performance.

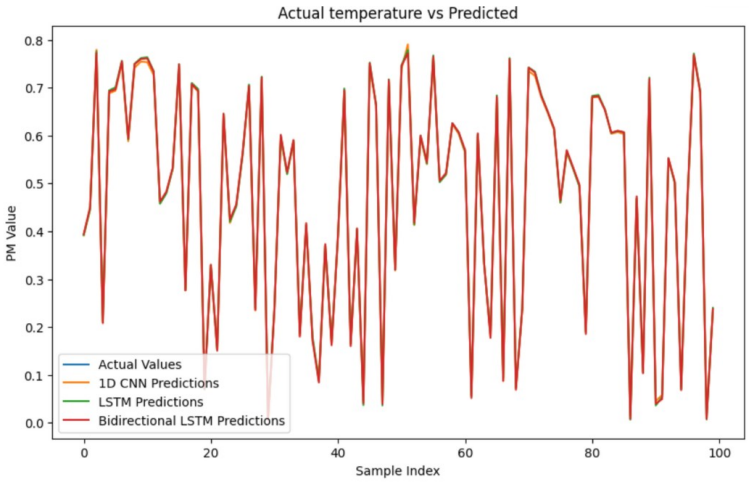


Figure 7: *actual rotor temperature vs predicted rotor temperature*

Conclusion

The objective of this project was to develop a Real-Time Intelligent Control System to Address Faults in DC Motors by predicting rotor temperature and implementing a feedback system to regulate motor input voltage. By accurately predicting the rotor temperature, we aimed to prevent motor overheating and extend its lifespan.

In pursuit of this objective, we trained two models: one to predict motor velocity and the other to predict angular velocity. Both models yielded satisfactory results, demonstrating minimal error and high r-squared

scores. Additionally, the third model, designed to predict rotor temperature, achieved outstanding accuracy, which we further enhanced by employing a bi-directional LSTM architecture.

The successful modeling of Permanent Magnet DC (PMDC) motors in this project underscores the potential of machine learning to significantly improve motor performance and longevity. Accurate temperature prediction allows for intelligent control, directly addressing the challenges associated with motor overheating.

However, due to time and resource constraints, we were unable to implement the reinforcement learning model necessary to complete the feedback cycle by adjusting input voltage based on rotor temperature in real time.

Future work should focus on incorporating the reinforcement learning model to close this feedback loop, enabling a fully autonomous control system. The practical applications of this system are vast, spanning industries that rely on DC motors—from cranes and conveyors to air compressors and toys. In scenarios with multiple motors, such a control system could dynamically adjust voltage among the motors, ensuring optimal performance even if one motor experiences overheating.

In conclusion, DC motors are integral to many fields and applications. Enhancing their performance and extending their lifespan would offer substantial economic benefits, making this research a valuable contribution to the field.

References

[1] Modukuru, P. (2020). PMSM Rotor Temperature Prediction. GitHub. https://github.com/pranaymodukuru/PMSM_Rotor_Temp_Prediction