CERTIFICATE

It is certified that the work contained in the thesis titled **"Data Driven Prognostic Methodology to Study the Failure of Motor"** by **"Ahin Banerjee"** has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. Degree.

Prof. Prabhat Kumar Singh Dikshit
(Supervisor & Chairman)
HOD, Department of Civil Engineering
Indian Institute of Technology (Banaras Hindu University)
Varanasi–221005

DECLARATION BY THE CANDIDATE

I, **Mr. Ahin Banerjee**, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of **Prof. Prabhat Kumar Singh Dikshit** at Department of Civil Engineering, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports dissertation, thesis, *etc*., or available at websites and have not included them in this thesis and have not cited as my own work.

Date:

Place: Varanasi (Ahin Banerjee)

CERTIFICATE BY THE SUPERVISOR

It is certified that the above statement made by the student is correct to the best of my/our knowledge.

Prof. Prabhat Kumar Singh Dikshit
(Supervisor)
Department of Civil Engineering
IIT (BHU), Varanasi- 221005

Prof. Prabhat Kumar Singh Dikshit
(Head of Department)
Department of Civil Engineering
IIT (BHU), Varanasi- 221005

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: **“Data Driven Prognostic Methodology to Study the Failure of Motor”.**

Name of the Student**: Mr. Ahin Banerjee**

Copyright Transfer

Date:

Place: Varanasi **(Ahin Banerjee)**

DEDICATED TO MY LOVING FAMILY

&

FRIENDS

ACKNOWLEDGEMENT

It is with great pleasure and felicity that I would like to express thanks to all people who have made this thesis possible.

I express my sincere gratitude and indebtness to my supervisor Dr. P. K. S. Dikshit, Professor and Head, Department of Civil Engineering, Indian Institute of Technology (Banaras Hindu University) at Varanasi. I would like to offer special thanks to my venerated late supervisor Dr. Sanjay Kumar Gupta, who, although no longer with us, continues to inspire me by his example and dedication he served over the course of his career. I feel privileged to express my deep sense of gratitude to both the supervisors for their valuable guidance, endless support and constant encouragement throughout the course of my research work. Their truly scientific intuition and broad vision inspired and enriched my growth as a student and researcher. The critical comments, rendered by them during the discussions are deeply acknowledged. I humbly acknowledge a lifetime gratitude to them.

The author expresses sincere thanks to Mr. Prasanta Sarkar, General Manager, Advanced Engineering Division, ERC TATA Motors, Pimpri-Chinchwad, Pune and Late Dr. S. K Gupta for their impetus of collaborative research work which provided the opportunity to carry out experiments in the highly sophisticated laboratory of TATA Motors. At TATA Motors, I gained exposure to the real-time problems faced by the industry and learnt the way to approach towards problem solving, therefore, gratitude is extended to TATA Motors.

I wish to express deep regards to Prof. Chandrasekhar Putcha, California State University, Fullerton, USA for his kind support at all moments during the progress of my research.

I am thankful to RPEC members Prof. Subir Das, Department of Applied Mathematics, and Dr. Supriya Mohanty, Department of Civil Engineering, Indian Institute of Technology (BHU) at Varanasi, for their valuable assessments of my research progress. I will be indebted for their continued support.

The cooperation and constant encouragements from my fellow friends: Rudra, Sayan, Jonak, Rana, Pinaki, Arpan, Swakshar, Subrata, Pankaj, Tanmoy, Debjit, Kasturi, Mohan, Sakshi, Hari, Krishna, Mannu, Ranjeesh, Verma, Nitesh, Bhupendra, Shivani, Mahato, Dr. Shasank, Dr. Ajay, Sameer, Deepak, Dr. Koushik, Jamal, Shubham Dixit, Andreas and juniors for the thoughtprovoking discussions, their support, and sincere help that made my stay in BHU a memorable one. Special thanks to my friends Pawan, Dilip, Amar Penta, Saalai Thenegan, Girish, Ketan, Gajanan, Ratheesh, Mansa, Sumit, Gitesh and Vaibhav during my stay at Pune, India. I feel lucky to be blessed with their wonderful comradeship.

My parents have been my best mentors, preparing me for life in its various aspects. There are no words to express my gratitude for all the selfless efforts they made. I would like to thank my wife Debanshee for her love, moral support and motivation during my research work. I would like to thank my elder brother Mr. Tuhin Banerjee for his love, moral support, encouragement and motivation to get me through my Ph.D.

Finally, I bow with reverence and gratitude to thank the almighty who has enriched me with such an excellent opportunity and infused the power in my mind to fulfill the work assigned to me.

Date:

Place: Varanasi (Ahin Banerjee)

ABSTRACT

The extensive use of high-end automated assets in an automotive sector is the current paradigm shift as a prerequisite of Industry 4.0. In tandem, the life cycle assessment is the prerequisite for such automated systems to optimize the return on this significant investment. Today's market places increasing emphasis on quality efficiency and environmental performance. Scientific understanding of the degradation process and its phenomena is essential for designing and achieving optimal performance. Even before designing high-performance, environmentally friendly gadgets, a product's life cycle optimization is critical. Machine downtime due to maintainability and system component replacement is quite often associated with elevated expenses. Present work is motivated towards developing a computationally efficient system health prognostics methodology directed towards enhanced performance within optimized cost and safety standards. System's health assessment under actual operating conditions and its future state prediction very often helps in developing an effective maintenance plan. Data-driven models are employed to take advantage of condition based maintenance (CBM), which provides an optimized maintenance strategy for estimating the system's remaining useful life (RUL).

The proposed work utilizes data driven models to predict the RUL of a clutch actuator motor in an electric automated manual transmission (*e*-AMT) application. In an *e*-AMT car, the electromechanical actuator works in tandem with a permanent magnet direct current (PMDC) motor to facilitate automated clutch operation, and any failure or decrease in performance of this motor potentially cause the vehicle to stall. Motor degradation is characterized by a deviation in their performance parameters from their initial values. The change in parameters in turn will cause degradation in performance of the clutch along with the motor which is a part of the clutch assembly, eventually leading to function failure of the system. Current methods for forecasting failures triggered by electronic component faults rely on defining monotonically deviating parameters and modeling their evolution over time. This dissertation establishes a prognostics approach that uses machine learning features derived for an electrical motor response to solve this issue. Exponential degradation modeling and the three variants of particle filter (PF) are applied in the development of an efficient reliability methodology for predicting automotive motor failure. Subsequently, the robust and reliable techniques for motor RUL prediction will support scheduling an optimal maintenance plan.

First, the degradation model to exhibit the state of health of the clutch was developed. The initial step has been in the selection of an appropriate prognostic parameter. Unusual patterns in the sensor data set collected from experiments indicated that current (I_a) is one such prognostic parameter to indicate the state of the health of the clutch. A novel condition indicator (CI) and a threshold for a conditionally independent noisy signal from the motor subjected to cumulative degradation were established. A dominating feature characterizing the motor health was discerned amongst time, frequency and time-frequency domain and identified while analyzing the time-series signal composed of an agglomeration of different frequencies that produce higher octaves. Tests for monotonocity and trendability metrics affirmed a distinguishing CI. Principal component analysis (PCA) allowed the fusion of features for the selection of the best-performing CI. The proposed CI was used in an exponential degradation model to predict the RUL of the motor accurately.

The second part of the thesis involves the application of three variants of particle filter (PF) with various resampling techniques to account for heavy-tailed observations and non-Gaussian characteristic of noise to improve the accuracy of RUL estimation. The prediction of the motor's RUL is pursued by a model-based filtering method that relies on an empirical model and a stochastic filtering technique. The empirical model describes the degradation in clutch health with the progression of the fault in a motor component. The stochastic filtering technique on the other hand was used to first solve the 'motor health state' estimation problem, followed by a prediction problem in which the estimated motor health state is extrapolated forward in time to predict RUL. A comparative analysis of the results showed major enhancement in the prediction accuracy respectively and in the efficacy of RUL estimation due to traditional PF, unscented particle filter (UPF), and improved unscented particle filters (*i*-UPF) vis-a-vis the ordinarily fitted exponential degradation model.

Further, the verification and validation of the prognostic models have been performed utilizing the benchmark Li-ion battery data from the repository of NASA, Prognostics Centre of Excellence (PCoE). The resulting accuracy within the existing 10% results itself validates the superiority of the proposed scheme. This work shows the effectiveness of adaptive filtering techniques towards efficient predictive maintenance (PdM) by employing analytics, which are methods and techniques that use asset data, such as condition and loading data, or experience, to detect or predict changes in the physical condition of the equipment. By integrating PdM in current industrial practices, the use of these analytics contributes to a larger shift towards Industry 4.0.

TABLE OF CONTENTS

Contents **Page No.**

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

The principal abbreviations used in this thesis are presented for easy reference. Additionally, most symbols are identified where they are used, or first used if use is different than given below.

List of Abbreviations	**Description**
RUL	remaining useful life
e-AMT	electric automated manual transmission
HIL	hardware-in-loop
ECU	electronic control unit
CBM	condition based maintenance
OEM	original equipment manufacturer
PdM	predictive maintenance
PHM	prognostics and health management
CPS	cyber physical systems
PMSM	permanent magnet synchronous motor
PMDC	permanent magnet direct current motor
CLR	cumulative loss ratio
PID	proportional integral derivative
SHM	structural health monitoring
FMEA	failure mode effect and analysis
CI	condition indicator
PF	particle filter
UPF	unscented particle filter
i-UPF	improved unscented particle filter
UT	unscented transform
NN	neural network
MLP	multi layered perceptron
GA	genetic algorithm
FFT	fast Fourier transform
MCSA	motor current signature analysis
PCA	principal component analysis
GMM	Gaussian mixture models

HMM	hidden Markov model
EKF	extended Kalman filter
UKF	unscented Kalman filter
EPF	extended particle filter
ESS	effective sample size
SPC	sequential Monte Carlo
TTF	time-to-failure
SOH/ SOC	state-of-health/ state-of-charge
EOL/ EOD	end-of-life/ end-of-discharge
ECM	electronic control modules
TCU	transmission control unit
PWM	pulse width modulation
ADAS	advanced driver assistance systems
ALCT	accelerated life cycle test
MIDC	modified Indian drive cycle
ESA	electrical signature analysis
FIR	feature importance ranking