TABLE OF CONTENTS

Contents	Page No.
Certificates	i-iii
Acknowledgement	v-vi
Abstract	vii-viii
Table of Content	
List of Table	xiii
List of Figures	xv-xviii
Nomenclature	xix-xx
Chapter 1	**1**
Introduction and Literature Review	**1**
1.1 Introduction to Electric Automated Manual Transmission (*e*-AMT) Technology	2
1.2 Motivation and Problem Statement	3
1.3 Literature Review	4
1.3.1 Maintenance Philosophy	5
1.3.2 Condition based Maintenance in Auto Industry	7
1.3.2.1 Time domain analysis	12
1.3.2.2 Frequency Domain Analysis	14
1.3.2.3 Time-Frequency Analysis	14
1.3.3 Modelling Approaches	16
1.3.3.1 Stochastic Modelling Approach	17
1.3.3.2 Adaptive Approach	19
1.4 Objectives of the Work	22
1.5 Organized Structure of the Thesis	22
Chapter 2	**25**
Remaining Useful Life Methodology	**25**
2.1 Introduction	25
2.2 Definition of RUL	27
2.3 Theory of RUL Estimation	27
2.4 Past RUL Works	32

Chapter 3 37

Experimental Setup and Data Acquisition 37

3.1 Introduction 37

3.2 Preparation of Experimental Setup 38

3.3 Data Generation 43

3.4 Role of Motor 47

3.4.1 Advantages of PMDC motor 47

3.5 Evaluation Criterion 50

Chapter-4 53

Data driven Methodology-Mathematical Background and Associated Computation 53

4.1 Introduction 53

4.2 Overview of the Data Pre-Processing 54

4.2.1 Data Processing 56

4.2.1.1 Feature Extraction 57

4.2.1.2 Smoothing 58

4.2.2 FIR and Health Indicator Determination 59

4.2.3 Feature Fusion using PCA 59

4.3 Stochastic Approach 61

4.3.1 Exponential Degradation Modelling and RUL Prediction 61

4.3.2 RUL Computation 62

4.4 Adaptive Filtering Technique 62

4.4.1 Particle Filter 63

4.4.2 Unscented Particle Filter and Improved Unscented Particle Filter 65

4.4.2.1 Unscented Particle Filter (UPF) 66

4.4.2.2 Improved Unscented Particle Filter (i-UPF) 68

4.4.3 Resampling Methodology 68

4.4.3.1 Multinomial resampling 69

4.4.3.2 Stratified resampling 69

4.4.3.3 Systematic resampling 70

4.4.3.4 Residual resampling 70

4.4.4 RUL Estimation Strategy 71

Chapter 5 73

Data Analysis for RUL Estimation 73

5.1 Introduction 73

5.2 Experimental Details 73

5.2.1 Waveforms of the Accelerated Life Cycle Test Data 74

5.2.1.1 Strategy I: (50%-70%) 75

5.2.1.2 Strategy II: (75%-80%) 77

5.2.1.3 Strategy III: (80%-85%) 81

5.3 Results and Discussion 84

5.3.1 Feature Extraction and Smoothing 84

5.3.2 FIR and Condition Indicator 87

5.3.3 Stochastic Approach 90

5.3.3.1 Exponential Degradation Model and RUL Computation 90

5.3.3.2 Performance Analysis 93

5.3.4 Adaptive filtering 96

5.3.4.1 Strategy-I: (50%-70%) 96

A. Particle Filter 97

B. Unscented Particle Filter 99

C. Improved Unscented Particle Filter 100

5.3.4.2 Strategy-II: (75%-80%) 102

A. Particle Filter 102

B. Unscented Particle Filter 104

C. Improved Unscented Particle Filter 105

5.3.4.3 Strategy-III: (80%-85%) 107

A. Particle Filter 107

B. Unscented Particle Filter 109

C. Improved Unscented Particle Filter 110

5.3.5 Comparison of Prognostic Accuracy Results 112

5.4 Summary 114

Chapter 6 115

Comparison of Particle Filter Variants towards RUL Estimation 115

6.1 Introduction 115

6.2 Results and Discussion 116
6.2.1 Comparative Results of Resampling Study 116
6.2.2 Optimal Choice of *c*-value 122
6.2.3 Comparative RUL prediction results of Strategy–I dataset 124
6.2.4 Comparative RUL prediction results of Strategy–II dataset 125
6.2.5 Comparative RUL prediction results of Strategy–III dataset 126
6.3 Verification and Validation 128
6.3.1 Battery Data Set - B0005 128
6.3.2 Battery Data Set - B0006 130
6.3.3 Battery Data Set - B0007 131
6.3.4 Battery Data Set - B0018 132
6.4 Summary 134

Chapter 7 135

Overall Conclusion and Future Scope of Work 135

7.1 Overall Conclusion 135
7.2 Future Scope of Work 136

References 139

About the Author 158

List of Publications 162

LIST OF TABLES

Table No.	Title	Page No.
Table 1.1	Industrial Maintenance Practices	5
Table 2.1	Data-driven prognostic models for RUL estimation	28
Table 3.1	Sensors used during experimentation	43
Table 3.2	Sample dataset from HIL experiment	46
Table 3.3	Specifications of Motor	49
Table 3.4	Specifications of Motor Controller	50
Table 4.1	List of extracted features considered in the study	57
Table 5.1	Empirically fitted values of the exponential degradation model	91
Table 5.2	Prognostic Accuracy Results	95
Table 5.3	Empirically fitted cubic polynomial parameters	96
Table 5.4	Empirically fitted parameters	102
Table 5.5	Empirically fitted parameters	107
Table 5.6	Prognostic Accuracy results for Strategy-I	112
Table 5.7	Prognostic Accuracy results for Strategy-II	113
Table 5.8	Prognostic Accuracy results for Strategy-III	113
Table 6.1	Comparison of Quantitative Resampling Results from Strategy-I	118
Table 6.2	Comparison of Quantitative Resampling Results from Strategy-II	119
Table 6.3	Comparison of Quantitative Resampling Results from Strategy-III	121
Table 6.4	Choice of best Resampling for Strategy-I dataset	124
Table 6.5	Choice of best Resampling for Strategy-II dataset	125
Table 6.6	Choice of best Resampling for Strategy-III dataset	126
Table 6.7	B0005-Prognostic Accuracy Results	130
Table 6.8	B0006-Prognostic Accuracy Results	131
Table 6.9	B0007-Prognostic Accuracy Results	132
Table 6.10	B0018-Prognostic Accuracy Results	134

LIST OF FIGURES

Figure No.	Title	Page No.
Fig. 1.1	*e*-AMT vehicle drive train	2
Fig. 1.2	*e*-AMT motor prognostics	3
Fig. 1.3	Increase in asset reliability in using PdM	7
Fig. 1.4	Visualizing the prognostics workflow to RUL as a decision making	8
Fig. 1.5	Diagram featuring Prognostics and Diagnostics	9
Fig. 1.6	Schematic of the major contributions	21
Fig. 2.1	Schematic of RUL Prediction	25
Fig. 2.2	Data-driven remaining useful life estimation approaches in the present study	28
Fig. 3.1	Components of an *e*-AMT set-up	37
Fig. 3.2	System Schematic of *e*-AMT consisting of ECU, Sensors and Actuators	39
Fig. 3.3	Transmission Control Unit Architecture	40
Fig. 3.4	Experimental Set-up	41
Fig. 3.5(a)	Schematic diagram of 12V, 0.5kW PMDC clutch motor actuator assembly with electronic control unit	44
Fig. 3.5(b)	Clutch sensor position during engagement-disengagement	44
Fig. 3.6(a)	PMDC Motor	48
Fig. 3.6(b)	Circuit diagram of a PMDC motor	48
Fig. 4.1	Schematic of data-driven RUL estimation methodologies	53
Fig. 4.2	Prognostics Protocol Module	55
Fig. 4.3	Flowchart of the proposed approach	56
Fig. 4.4	Illustration of particle filter variants in motor health prognosis	63
Fig. 5.1	Sample representation of a 50% -70% duty cycle input to the motor	75
Fig. 5.2	Sample representation of motor current response for 50% -70% duty cycle	75
Fig. 5.3	Sample plot of actuator position (degrees) during 50% -70% duty cycle	76
Fig. 5.4(a)	Magnified sample plot representing clutch Disengagement	76
Fig. 5.4(b)	Magnified sample plot representing clutch Engagement	76
Fig. 5.5	Variation of duty, current and actuator position for a sample clutch engagement cycle	77
Fig. 5.6	Variation of duty, current and actuator position for a sample clutch dis-engagement cycle	77
Fig. 5.7	Sample representation of a 75% -80% duty cycle input to the motor	78

Fig. 5.8	Sample representation of motor current response for 75% -80% duty cycle	78
Fig. 5.9	Sample plot of actuator position (degrees) during 75% -80% duty cycle	79
Fig. 5.10(a)	Magnified sample plot representing clutch Disengagement	79
Fig. 5.10(b)	Magnified sample plot representing clutch Engagement	79
Fig. 5.11	Variation of duty, current and actuator position for a sample clutch engagement cycle	80
Fig. 5.12	Variation of duty, current and actuator position for a sample clutch dis-engagement cycle	80
Fig. 5.13	Sample representation of an 80% -85% duty cycle input to the motor	81
Fig. 5.14	Sample representation of motor current response for 80% -85% duty cycle	82
Fig. 5.15	Sample plot of actuator position (degrees) during 80% -85% duty cycle	82
Fig. 5.16(a)	Magnified sample plot representing clutch Disengagement	83
Fig. 5.16(b)	Magnified sample plot representing clutch Engagement	83
Fig. 5.17	Variation of duty, current and actuator position for a sample clutch engagement cycle	83
Fig. 5.18	Variation of duty, current and actuator position for a sample clutch engagement cycle	84
Fig. 5.19	Steps of data pre-processing	85
Fig. 5.20(a)	Smoothened features of the sensor data using classical time domain, frequency domain and time-frequency domain methods Strategy-I	86
Fig. 5.20(b)	Smoothened features of the sensor data using classical time domain, frequency domain and time-frequency domain methods Strategy-II	86
Fig. 5.20(c)	Smoothened features of the sensor data using classical time domain, frequency domain and time-frequency domain methods Strategy-III	87
Fig. 5.21(a)	Ranking of the important pre-processed features Strategy-I	88
Fig. 5.21(b)	Ranking of the important pre-processed features Strategy-II	88
Fig. 5.21(c)	Ranking of the important pre-processed features Strategy-III	89
Fig. 5.22	Condition indicators for all three strategies obtained after feature fusion	90
Fig. 5.23	Bayesian updating of model parameters	91
Fig. 5.24(a)	Predicted RUL using exponential degradation model Strategy-I	92
Fig. 5.24(b)	Predicted RUL using exponential degradation model Strategy-II	92

Fig. 5.24(c)	Predicted RUL using exponential degradation model Strategy-III	92
Fig. 5.25(a)	Plot of estimated RUL and true RUL for Strategy-I	94
Fig. 5.25(b)	Plot of estimated RUL and true RUL for Strategy-II	94
Fig. 5.25(c)	Plot of estimated RUL and true RUL for Strategy-III	95
Fig. 5.26	State prediction scheme using Particle Filter for Strategy-I	98
Fig. 5.27	Histogram of RUL for Strategy-I	98
Fig. 5.28	State prediction scheme using Unscented Particle Filter for Strategy-I	99
Fig. 5.29	Histogram of RUL for Strategy-I	100
Fig. 5.30	State prediction scheme using Improved Unscented Particle Filter for Strategy-I	101
Fig. 5.31	Histogram of RUL for Strategy-I	101
Fig. 5.32	State prediction scheme using Particle Filter for Strategy-II	103
Fig. 5.33	Histogram of RUL for Strategy-II	103
Fig. 5.34	State prediction scheme using Unscented Particle Filter for Strategy-II	104
Fig. 5.35	Histogram of RUL for Strategy-II	105
Fig. 5.36	State prediction scheme using Improved Unscented Particle Filter for Strategy-II	106
Fig. 5.37	Histogram of RUL for Strategy-II	106
Fig. 5.38	State prediction scheme using Particle Filter for Strategy-III	108
Fig. 5.39	Histogram of RUL for Strategy-III	108
Fig. 5.40	State prediction scheme for Unscented Particle Filter for Strategy-III	109
Fig. 5.41	Histogram of RUL for Strategy-III	110
Fig. 5.42	State prediction scheme for Improved Unscented Particle Filter for Strategy-III	111
Fig. 5.43	Histogram of RUL for Strategy-III	111
Fig. 6.1	Comparison of resampling plots in case of *i*-UPF for Strategy-I dataset	119
Fig. 6.2	Comparison of resampling plots in case of *i*-UPF for Strategy-II dataset	120
Fig. 6.3	Comparison of resampling plots in case of *i*-UPF for Strategy-III dataset	122
Fig. 6.4	Optimal choice of *c*-value for Strategy-I	123
Fig. 6.5	Optimal choice of *c*-value for Strategy-II	123
Fig. 6.6	Optimal choice of *c*-value for Strategy-III	123
Fig. 6.7	Comparison of PF, UPF and *i*-UPF using Strategy-I dataset for motor RUL prediction	125
Fig. 6.8	Comparison of PF, UPF and *i*-UPF using Strategy-II dataset for motor RUL prediction	126

Fig. 6.9	Comparison of PF, UPF and *i*-UPF using Strategy-III dataset for motor RUL prediction	127
Fig. 6.10(a)	PF based state prediction for B0005 battery	129
Fig. 6.10(b)	PF based RUL estimation for B0005 battery	129
Fig. 6.11(a)	UPF based state prediction for B0005 battery	129
Fig. 6.11(b)	UPF based RUL estimation for B0005 battery	129
Fig. 6.12(a)	*i*-UPF based state prediction for B0005 battery	129
Fig. 6.12(b)	*i*-UPF based RUL estimation for B0005 battery	129
Fig. 6.13(a)	PF based state prediction for B0006 battery	130
Fig. 6.13(b)	PF based RUL estimation for B0006 battery	130
Fig. 6.14(a)	UPF based state prediction for B0006 battery	130
Fig. 6.14(b)	UPF based RUL estimation for B0006 battery	130
Fig. 6.15(a)	*i*-UPF based state prediction for B0006 battery	131
Fig. 6.15(b)	*i*-UPF based RUL prediction for B0006 battery	131
Fig. 6.16(a)	PF based state prediction for B0007 battery	131
Fig. 6.16(b)	PF based RUL estimation for B0007 battery	131
Fig. 6.17(a)	UPF based state prediction for B0007 battery	132
Fig. 6.17(b)	UPF based RUL estimation for B0007 battery	132
Fig. 6.18(a)	*i*-UPF based state prediction for B0007 battery	132
Fig. 6.18(b)	*i*-UPF based RUL prediction for B0007 battery	132
Fig. 6.19(a)	PF based state prediction for B0018 battery	133
Fig. 6.19(b)	PF based RUL estimation for B0018 battery	133
Fig. 6.20(a)	UPF based state prediction for B0018 battery	133
Fig. 6.20(b)	UPF based RUL estimation for B0018 battery	133
Fig. 6.21(a)	*i*-UPF based state prediction for B0018 battery	133
Fig. 6.21(b)	*i*-UPF based RUL prediction for B0018 battery	133