



Faculty of Manufacturing Engineering

**SUPER TWISTING SLIDING MODE CONTROLLERS AND
KALMAN-BUCY FILTER FOR SINGLE AXIS POSITIONING
SYSTEM**

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**SUPER TWISTING SLIDING MODE CONTROLLERS AND KALMAN-BUCY
FILTER FOR SINGLE AXIS POSITIONING SYSTEM**

CHIEW TSUNG HENG

**A thesis submitted
in fulfillment of the requirements for the degree of Doctor of Philosophy**

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DECLARATION

I declare that this thesis entitle “Super Twisting Sliding Mode Controllers and Kalman-Bucy Filter for Single Axis Positioning System” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name :

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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Doctor of Philosophy.

Signature :

Name :

Date :

DEDICATION

To my beloved father and mother

Their loving and unconditional support throughout my life

and

For those I love very much

ABSTRACT

Demands for accuracy and precision in machine tools have generated great interests for development of high performance drive control system with excellent characteristics in reference tracking, chattering, and robustness against input disturbance and load variation. Recently, a nonlinear control approach named super twisting sliding mode controller (ST-SMC) becomes attractive for its ability to meet complex demands on system performance where classical controllers have failed to meet. ST-SMC provides good tracking quality and effectively proven disturbance rejection property. However, chattering still exist as an issue in application of ST-SMC. To-date, there exists a knowledge gap in in-depth analyses on optimal design of gains parameters in control laws of ST-SMC constituting trade-off between tracking accuracy and effect of chattering. This thesis presents optimal design of ST-SMC with enhanced smoothening functions for precise tracking performances and reduced chattering; validated on a single axis sliding unit with direct driven linear motor. In addition, a Kalman-Bucy filter (KBF) was designed and applied to estimate velocity signal for the control system thus eliminating effect of noise amplification normally associated with numerical differentiation of position signal. A Taguchi optimization method was applied to optimize the control laws gain parameters of ST-SMC based on three performance indexes, namely; root mean square of tracking error (RMSE), chattering amplitude reduction in frequency domain, and variations in RMSE values from exposure to input disturbance. The optimal values of the gain parameters L and W were 0.7 and 10×10^{-5} respectively; with a confidence level of 95%. Two variants of ST-SMC were formulated based on modifications of the control laws of original ST-SMC; where the signum function was replaced by either a hyperbolic tangent function or an arc-tangent smoothening function to a form hyperbolic ST-SMC (HST-SMC) and an arc-tangent ST-SMC (Arc-ST-SMC) respectively. Five controllers were designed and validated experimentally, namely; cascade P/PI controller, pseudo-SMC, optimized ST-SMC, HST-SMC, and Arc-ST-SMC. The control performances of each controller were analyzed with respect to tracking accuracy, chattering suppression, and robustness against input disturbance and system dynamics variation. The optimized ST-SMC produced the best overall control performance with 9.6% (RMSE), 3.9% (disturbance rejection), and 13.4% (robustness) superior results compared to the other variants of SMC-based controllers. On the other hand, HST-SMC produced a comparable tracking performance to optimized ST-SMC with minimal difference of 7.3% (RMSE), 0.4% (disturbance rejection), and 0.7% (robustness). HST-SMC offers a fair trade-off in control performance between tracking accuracy, disturbance rejection and chattering attenuation. Arc-ST-SMC showed its strength with a significant 71.4% reduction in chattering effect. Finally, this thesis has demonstrated outstanding control performances of ST-SMC-based controllers that produced tracking accuracy that was 96.0% better than classical cascade P/PI controller.

ABSTRAK

Permintaan terhadap ketepatan dan kejituan pada perkakasan mesin telah menjana minat yang besar terhadap sistem kawalan pemacu berprestasi tinggi dengan ciri cemerlang berkaitan penjejakan rujukan, gelantuk, dan keteguhan terhadap gangguan input dan variasi beban. Kebelakangan ini, kaedah kawalan tidak lurus dikenali sebagai pengawal mod gelongsor pemusingan super (ST-SMC) menjadi tarikan kerana keupayaannya memenuhi permintaan kompleks pada prestasi sistem yang gagal dicapai oleh pengawal klasik. ST-SMC menawarkan kualiti pengesanan yang baik di samping keupayaan penolakan gangguan yang terbukti berkesan. Walau bagaimanapun, gelantuk masih wujud sebagai satu isu dalam aplikasi ST-SMC. Hingga kini wujud jurang pengetahuan terhadap analisa mendalam pada reka bentuk optima parameter peraturan kawalan ST-SMC melibatkan keseimbangan antara ketepatan pengesanan dan kesan gelantuk. Tesis ini membentangkan reka bentuk optimum ST-SMC dengan fungsi pelicin yang dipertingkatkan untuk prestasi pengesanan yang jitu dan pengurangan kesan gelantuk; disahkan pada paksi tunggal unit gelangsar pemacu terus motor lurus. Di samping itu, penapis Kalman-Bucy (KBF) direka dan digunakan untuk menganggarkan isyarat halaju pada sistem kawalan bagi mengelakkan kesan amplifikasi bunyi yang biasanya wujud melalui pembezaan berangka isyarat kedudukan. Kaedah pengoptimuman Taguchi digunakan untuk mengoptimumkan parameter-parameter kawalan ST-SMC berpandukan kepada tiga indeks prestasi, iaitu; ralat purata punca kuasa dua (RMSE), pengurangan amplitud gelantuk dalam domain frekuensi, dan variasi dalam nilai RMSE daripada pendedahan kepada gangguan input. Nilai optimum yang dikenalpasti bagi parameter L dan W adalah 0.7 dan 10×10^{-5} berdasarkan tahap keyakinan 95%. Dua variasi ST-SMC telah dirumuskan berdasarkan pengubahsuaian terhadap peraturan kawalan ST-SMC; di mana fungsi signum digantikan oleh fungsi tangen hiperbolik atau fungsi arc-tangen untuk membentuk hiperbolik ST-SMC (HST-SMC) dan arc-tangen ST-SMC (Arc-ST-SMC). Lima pengawal telah direka dan disahkan secara ujikaji, iaitu; pengawal lata P/PI , pseudo-SMC, ST-SMC optimum, HST-SMC, dan Arc-ST-SMC. Prestasi kawalan setiap pengawal dianalisa berdasarkan ketepatan pengesanan, pengurangan gelantuk, dan keteguhan terhadap gangguan input dan variasi sistem dinamik. ST-SMC optimum menghasilkan prestasi kawalan keseluruhan yang terbaik iaitu 9.6% (RMSE), 3.9% (penolakan gangguan), dan 13.4% (keteguhan) lebih baik berbanding dengan varian-varian pengawal berasaskan SMC yang lain. Sebaliknya, HST-SMC menghasilkan prestasi pengesanan yang setanding dengan ST-SMC optimum dengan perbezaan minimum sebanyak 7.3% (RMSE), 0.4% (penolakan gangguan), dan 0.7% (keteguhan). HST-SMC menawarkan keseimbangan antara ketepatan pengesanan, penolakan gangguan dan pengurangan gelantuk. Arc-ST-SMC pula menunjukkan kekuatannya dengan penurunan ketara sebanyak 71.4% kesan gelantuk. Akhirnya, tesis ini juga telah menunjukkan kecemerlangan prestasi kawalan pengawal-pengawal berasaskan ST-SMC yang menghasilkan ketepatan pengesanan sebanyak 96.0% lebih baik daripada pengawal klasik lata P/PI .

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TABLE OF CONTENTS

	PAGE
DECLARATION	
APPROVAL	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vii
LIST OF FIGURES	xi
LIST OF APPENDICES	xviii
LIST OF ABBREVIATIONS	xix
LIST OF SYMBOLS	xxii
LIST OF PUBLICATIONS	xxvii
CHAPTER	
1. INTRODUCTION	1
1.1 Background	1
1.2 Problem Statement	2
1.3 Objectives	4
1.4 Research Scopes and Limitations	4
1.5 Overview of Thesis	5
2. LITERATURE REVIEW	7
2.1 Introduction	7
2.2 Machine Tools Technology	8
2.3 Mechanical Drive Systems	8
2.3.1 Rack and Pinion	8
2.3.2 Ball Screw Drive System	10
2.3.3 Linear Drive System	11
2.4 Performance Measures for Machine Tools Drive System	14
2.4.1 Performance Measures in Time Domain Response	15
2.4.2 Performance Measures in Frequency Domain Response	17
2.5 Disturbance Forces in Machine Tools Application	19
2.5.1 Disturbance Cutting Force	20
2.5.2 Disturbance Friction Force	22
2.5.2.1 Static Friction Model	24
2.5.2.2 Dahl Model	25
2.5.2.3 LuGre Model	26
2.5.2.4 GMS Model	27
2.6 Classical Control Techniques	30
2.6.1 PID Controller	30
2.6.2 Cascade Controllers	37
2.6.3 Models Feedforward	40
2.7 Advanced Control Techniques	42
2.7.1 N-PID Controller	42

2.7.2	H-infinity Controller	44
2.7.3	Sliding Mode Controller (SMC)	47
2.7.4	Second Order Sliding Mode Controller (SOSMC)	51
2.8	State Estimations Techniques	59
2.8.1	Disturbance Observers	60
2.8.2	Kalman Filter	63
2.8.2.1	Theoretical Backgrounds	63
2.8.2.2	Applications of Kalman Filters	65
2.9	Knowledge Gap	67
2.10	Summary	71
3.	METHODOLOGY	73
3.1	Introduction	73
3.2	Experimental Setup	75
3.3	System Identification and Modeling	77
3.4	Motor Constant Identification	81
3.5	Design of Kalman-Bucy Filter (KBF)	82
3.6	Design of Controllers	86
3.6.1	Design of Cascade P/PI Position Controller	87
3.6.2	Design of Sliding Mode Based Controllers	89
3.6.3	Optimization of Controller Gains using Taguchi Method	90
3.7	Philosophy of Proposed Control Algorithm	92
3.8	Summary	95
4.	DESIGN OF CONTROLLERS	97
4.1	Introduction	97
4.2	Design and Analysis of Cascade P/PI	98
4.2.1	Design and Analyses of Velocity Control Loop	99
4.2.2	Design and Analyses of Position Control Loop	103
4.2.3	Controller Design Validation	107
4.3	Design of Sliding Mode Controller (SMC)	108
4.3.1	Switching Function of SMC	109
4.3.2	Control Laws of SMC	110
4.3.3	Stability Analysis of SMC	111
4.4	Design of Super Twisting Sliding Mode Controller (ST-SMC)	112
4.4.1	Switching Function of ST-SMC	112
4.4.2	Control Laws of ST-SMC	113
4.4.3	Stability Analysis of ST-SMC	113
4.5	Gains Optimization of ST-SMC using Taguchi Method	114
4.5.1	Determination of Orthogonal Array	115
4.5.2	Conduct of Experiments	116
4.5.3	Data Transformation using Signal-to-Noise Ratio	117
4.5.4	Analysis of the Main Effect Plot	119
4.5.5	Analysis of Variance (ANOVA)	123
4.5.6	Confirmation Test	126
4.5.7	Comparison in Performances between Optimized and Non-optimized ST-SMC	128
4.6	Modification on ST-SMC	131
4.7	Summary	133

5.	RESULTS AND DISCUSSION	135
5.1	Introduction	135
5.2	Control Performances of Cascade P/PI Controller	136
5.3	Control Performances of Pseudo-SMC	142
5.4	Control Performances of Optimized ST-SMC	145
5.5	Control Performances of ST-SMC Variants	148
	5.5.1 ST-SMC using Hyperbolic Tangent Function (HST-SMC)	149
	5.5.2 ST-SMC using Arc-tangent Function (Arc-ST-SMC)	151
5.6	Discussion on Control Performances	154
	5.6.1 Maximum Tracking Errors and RMSE	155
	5.6.2 Chattering Effect	164
	5.6.3 Input Disturbance Rejection	168
	5.6.4 Robustness against Load Variation	172
5.7	Summary	174
6.	CONCLUSION	181
6.1	Introduction	181
6.2	Significance of Study	185
6.3	Future Works	186
	REFERENCES	187
	APPENDICES	212

LIST OF TABLES

TABLE	TITLE	PAGE
2.1	Effects of independent gain P, I, and D on overall time domain response	31
2.2	Characteristics and drawbacks of different filters	65
2.3	Strengths and weaknesses of reviewed state estimation control techniques	67
2.4	Strengths and weaknesses of reviewed classical and advanced control techniques	68
3.1	Parameters of system model	80
3.2	Weaknesses and proposed solutions to original ST-SMC	93
4.1	Gain values of K_p , and K_i for PI controller in velocity loop	100
4.2	Control factors of ST-SMC with respective ranges and values at three levels	116
4.3	The orthogonal array of L_9	116
4.4	S/N ratio for RMSE responses	118
4.5	S/N ratio for chattering amplitude responses at 2000 Hz	118
4.6	S/N ratio for RMSE variation responses during the presence of disturbance	119
4.7	Factor level average for RMSE, chattering amplitude at 2000 Hz,	121

	and RMSE variation responses	
4.8	Summary on results of main effect plots for performance indexes responses	122
4.9	ANOVA table for RMSE responses	123
4.10	ANOVA table for chattering amplitude responses at 2000 Hz	124
4.11	ANOVA table for responses of RMSE variation	124
4.12	Summary of calculated parameters, expected mean performances and confidence intervals at optimum condition for RMSE responses, chattering amplitude responses at 2000 Hz, and responses of RMSE variation	127
4.13	Comparison in results on RMSE responses, chattering amplitude at 2000 Hz, and responses of RMSE variation between optimized ST-SMC and non-optimized ST-SMC	130
5.1	Tracking performances of cascade P/PI controller	137
5.2	RMSE variations of cascade P/PI controller with and without the presence of input disturbance	141
5.3	RMSE variations of cascade P/PI controller with varying load values	141
5.4	Tracking performances of pseudo-SMC	143
5.5	RMSE variations of pseudo-SMC controller with and without the presence of input disturbance	144
5.6	RMSE variations of pseudo-SMC controller with varying load values	144
5.7	Tracking performances of optimized ST-SMC	146

5.8	RMSE variations of optimized ST-SMC controller with and without the presence of input disturbance	148
5.9	RMSE variations of optimized ST-SMC controller with varying load values	148
5.10	Tracking performances of ST-SMC variant using hyperbolic tangent	150
5.11	RMSE variations of HST-SMC controller with and without the presence of input disturbance	151
5.12	RMSE variations of HST-SMC controller with varying load values	151
5.13	Tracking performances of Arc-ST-SMC	152
5.14	RMSE variations of Arc-ST-SMC controller with and without the presence of input disturbance	154
5.15	RMSE variations of Arc-ST-SMC controller with varying load values	154
5.16	Maximum tracking errors and RMSE values of five different controllers for input reference signal of 20 mm amplitude and 0.5 Hz frequency	156
5.17	Maximum tracking errors and RMSE values of five different controllers for input reference signal of 20 mm amplitude and 1.0 Hz frequency	157
5.18	Maximum tracking errors and RMSE values of five different controllers for input reference signal of 5 mm amplitude and 5.0 Hz frequency	160
5.19	Comparison in maximum tracking errors and RMSE values of	162

	SMC-based controllers for input reference of amplitude 20 mm at 0.5 Hz	
5.20	Comparison in maximum tracking errors and RMSE values of SMC-based controllers for input reference of amplitude 20 mm at 1.0 Hz	162
5.21	Maximum amplitudes of FFT for different families of SMC	167
5.22	Measured RMSE values of SMC-based controllers with and without the presence of disturbance for input reference of amplitude 20 mm at 0.5 Hz	171
5.23	Measured RMSE values of SMC-based controllers with and without the presence of disturbance for input reference of amplitude 20 mm at 1.0 Hz	171
5.24	RMSE values of SMC-based controllers against load variation at tracking frequency of 0.5 Hz	173
5.25	RMSE values of SMC-based controllers against load variation at tracking frequency of 1.0 Hz	173
5.26	Summary of control performances for different variants of sliding mode controllers	178

LIST OF FIGURES

FIGURE	TITLE	PAGE
2.1	Rack and pinion system	9
2.2	Ball screw drive system	10
2.3	Linear drive system	12
2.4	Structure of iron-core linear motor	12
2.5	PTP motion and continuous motion	14
2.6	Step response of a second order system	15
2.7	A step response with zero steady-state error for output 1, and finite steady-state error $e_2(\infty)$ for output 2	16
2.8	A simple block diagram of controlled drive system illustrating actual output and input disturbance forces	17
2.9	Comparison between (a) reference input and actual output signals with corresponding (b) tracking error	18
2.10	Resonance caused by bolts placement that hold machine to the ground	19
2.11	Force circle of cutting zone	20
2.12	Spectral analysis of cutting force during milling process	22
2.13	Formation of spikes known as quadrant glitches during circular motion	23

2.14	Pre-sliding and sliding regimes of friction force	24
2.15	Different friction components in static friction model	25
2.16	Maxwell-slip structure with parallel N -elementary	28
2.17	Block diagram of a basic feedback control system	32
2.18	Control structure of (a) PI-D controller and (b) I-PD controller	36
2.19	The contour error modeling and control structure of CCC	37
2.20	A typical cascade control scheme	38
2.21	A general block diagram of model-based control technique	40
2.22	Block diagram of N-PID controller in feedback system	43
2.23	The general control configuration to synthesize controller using H-infinity	45
2.24	Chattering phenomenon	49
2.25	Characteristic of ideal and pseudo sliding motion	50
2.26	A general block diagram of state estimation technique	60
2.27	Summary of literature review	72
3.1	Flow chart of overall research	74
3.2	Single axis direct driven positioning system developed by Googol Technology	75
3.3	Configuration of overall experimental setup	76
3.4	Graphical user interface developed from ControlDesk software	77
3.5	Simulink diagram of FRF measurement	78
3.6	Sample data of (a) measured input voltage, and (b) output position	78
3.7	Measured FRF of single axis positioning system	79
3.8	Measured FRF and fitted second order model with time delay	79

3.9	Pole-zero mapping of system model	80
3.10	Block diagram of open loop system for estimation of force constant	81
3.11	Structure of KBF	84
3.12	Block diagram to investigate quality of estimated velocity and velocity obtained from direct differentiation of position	84
3.13	Velocity signal obtained using (a) direct differentiation of measured position signal, and (b) KBF	85
3.14	Velocity errors between direct differentiation of position and estimation using KBF	85
3.15	General design processes of cascade P/PI controller	88
3.16	General design process of SMC	89
3.17	General procedures for gain optimization of ST-SMC	91
3.18	Philosophy of proposed algorithm that combined both ST-SMC and KBF	93
4.1	Block diagram of the general control structure for cascade P/PI controller	98
4.2	Block diagram of velocity control loop	99
4.3	Bode diagram of velocity open loop transfer function with gain margin of 7.71 dB at 231 Hz and phase margin of 78° at 77.6 Hz	101
4.4	Nyquist plot of the velocity open loop transfer function	101
4.5	Bode diagram of velocity closed-loop transfer function	102
4.6	Sensitivity function of the velocity loop	103
4.7	Bode diagram of position open loop transfer function with a gain	105

	margin of 9.23 dB and a phase margin of 53.6°	
4.8	Bode diagram of position closed-loop transfer function	105
4.9	Sensitivity function of position control loop	106
4.10	Nyquist plot of position control loop	106
4.11	Peak value of magnitude plot for position closed-loop transfer function	107
4.12	Peak value of magnitude plot for sensitivity function of the position loop	107
4.13	Position error transfer function (left) and measured tracking error (right)	108
4.14	The general control scheme of SMC	109
4.15	Characteristics of signum function	111
4.16	The main effect plot of RMSE responses	120
4.17	The main effect plot of chattering amplitude responses at 2000 Hz	120
4.18	The main effect plot of responses for RMSE variation	121
4.19	Bar charts of (a) RMSE, (b) chattering amplitude, and (c) variation of RMSE for optimized ST-SMC (L2,W3), ST-SMC (L1, W3), and ST-SMC (L3, W3)	129
4.20	FFT of control command input signal for (a) optimized ST-SMC (L2, W3), (b) ST-SMC (L1, W3), and (c) ST-SMC (L3, W3)	129
4.21	Comparison between signum function and a hyperbolic tangent function at near zero regions of s -functions	131
4.22	Comparison between signum function and the arc-tangent smoothing function at near zero regions of s -functions	133

5.1	Reference input position with corresponding tracking errors for cascade P/PI controller using reference input frequencies of (a) 0.5 Hz, and (b) 1.0 Hz	137
5.2	Reference input position and actual output position at tracking frequency of 0.5 Hz at (a) zero position and (b) peak position	138
5.3	Reference position signal of amplitude 20 mm and frequency 0.5 Hz with corresponding control command input signal	139
5.4	Measured dynamic stiffness of cascade P/PI controller	140
5.5	Reference input position with corresponding tracking errors for pseudo-SMC using reference input frequencies of (a) 0.5 Hz, and (b) 1.0 Hz	143
5.6	Control command input signal for pseudo-SMC	143
5.7	Reference input position with corresponding tracking errors for optimized ST-SMC using reference input frequencies of (a) 0.5 Hz, and (b) 1.0 Hz	146
5.8	Control command input signal for optimized ST-SMC	147
5.9	Reference input position with corresponding tracking errors for HST-SMC using reference input frequencies of (a) 0.5 Hz, and (b) 1.0 Hz	149
5.10	Control command input signal for HST-SMC	150
5.11	Reference input position with corresponding tracking errors for Arc-ST-SMC using reference input frequencies of (a) 0.5 Hz, and (b) 1.0 Hz	152
5.12	Control command input signal for Arc-ST-SMC	153

5.13	Measured tracking errors of (a) cascade P/PI controller, (b) pseudo-SMC, (c) optimized ST-SMC, (d) HST-SMC, and (e) Arc-ST-SMC for input reference signal of 20 mm amplitude and 0.5 Hz frequency	155
5.14	Measured tracking errors of (a) cascade P/PI controller, (b) pseudo-SMC, (c) optimized ST-SMC, (d) HST-SMC, and (e) Arc-ST-SMC for input reference signal of 20 mm amplitude and 1.0 Hz frequency	156
5.15	Measured tracking errors of (a) cascade P/PI controller, (b) pseudo-SMC, (c) optimized ST-SMC, (d) HST-SMC, and (e) Arc-ST-SMC for input reference signal of 5 mm amplitude and 5.0 Hz frequency	159
5.16	Comparison in tracking errors produced by (a) pseudo-SMC, (b) optimized ST-SMC, (c) HST-SMC, and (d) Arc-ST-SMC for input reference amplitude of 20 mm at 0.5 Hz	161
5.17	Comparison in tracking errors produced by (a) pseudo-SMC, (b) optimized ST-SMC, (c) HST-SMC, and (d) Arc-ST-SMC for input reference amplitude of 20 mm at 1.0 Hz	161
5.18	Comparison of signum function with (a) hyperbolic tangent function, and (b) arc-tangent smoothening function	164
5.19	Control command input signals of (a) pseudo-SMC, (b) optimized ST-SMC, (c) HST-SMC, and (d) Arc-ST-SMC	165
5.20	FFTs of control command input signals at high frequency regions for (a) pseudo-SMC, (b) optimized ST-SMC, (c) HST-SMC, and	167

	(d) Arc-ST-SMC	
5.21	Signals produced by band-limited white noise source	169
5.22	Measured dynamic stiffness of pseudo-SMC, optimized ST-SMC, HST-SMC and Arc-ST-SMC	170
5.23	Maximum tracking error of four variants of SMC-based controllers	176
5.24	RMSE values of four variants of SMC-based controllers	176
5.25	Chattering amplitude based on FFT measurements four variants of SMC-based controllers	177
5.26	Percentage of variation against disturbance noise input of four variants of SMC-based controllers	177
5.27	Percentage of variation against load variation of four variants of SMC-based controllers	178
5.28	Signum function and two different smoothening functions applied in the control laws of ST-SMC	179

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Specification of single axis positioning system	212
B	Sample data of measured input voltage and output position for system identification	213
C	Simulink block diagram of designed controllers	214
D	Design of super twisting algorithm for chattering suppression in machine tools	218
E	Design and analysis of super twisting sliding mode control for machine tools	219
F	Friction compensation techniques towards sustainability in machine tools: a review	220

LIST OF ABBREVIATIONS

ADC	-	Analog digital converter
ANOVA	-	Analysis of variance
Arc-ST-SMC	-	Arc-tangent super twisting sliding mode controller
AUV	-	Autonomous underwater vehicle
CCC	-	Cross-coupling controller
CNC	-	Computer numerical control
D	-	Derivative
DC	-	Direct current
DOF	-	Degree of freedom
DSP	-	Digital analog converter
EKBF	-	Extended Kalman-Bucy filter
EKF	-	Extended Kalman filter
ESA	-	Ecological system algorithm
FFT	-	Fast Fourier transform
FRF	-	Frequency response function
GMS	-	Generalized Maxwell-slip
GUI	-	Graphical user interface
HOSMC	-	Higher order sliding mode controller
HST-SMC	-	Hyperbolic super twisting sliding mode controller