

# Contents

<b>1</b>	<b>Introduction: Intuitive Theory of Sliding Mode Control</b>	<b>1</b>
1.1	Main Concepts of Sliding Mode Control	3
1.2	Chattering Avoidance: Attenuation and Elimination	9
1.2.1	Chattering Elimination: Quasi-Sliding Mode	9
1.2.2	Chattering Attenuation: Asymptotic Sliding Mode	11
1.3	Concept of Equivalent Control	17
1.4	Sliding Mode Equations	18
1.5	The Matching Condition and Insensitivity Properties	19
1.6	Sliding Mode Observer/Differentiator	20
1.7	Second-Order Sliding Mode	23
1.8	Output Tracking: Relative Degree Approach	27
1.8.1	Conventional Sliding Mode Controller Design	28
1.8.2	Integral Sliding Mode Controller Design	30
1.8.3	Super-Twisting Controller Design	33
1.8.4	Prescribed Convergence Law Controller Design	36
1.9	Notes and References	40
1.10	Exercises	41
<b>2</b>	<b>Conventional Sliding Modes</b>	<b>43</b>
2.1	Introduction	43
2.1.1	Filippov Solution	44
2.1.2	Concept of Equivalent Control	47
2.2	State-Feedback Sliding Surface Design	50
2.2.1	Regular Form	53
2.2.2	Eigenvalue Placement	55
2.2.3	Quadratic Minimization	58
2.3	State-Feedback Relay Control Law Design	61
2.3.1	Single-Input Nominal Systems	61
2.3.2	Single-Input Perturbed Systems	62
2.3.3	Relay Control for Multi-input Systems	67

2.4	State-Feedback Unit-Vector Control .....	68
2.4.1	Design in the Presence of Matched Uncertainty .....	68
2.4.2	Design in the Presence of Unmatched Uncertainty .....	71
2.5	Output Tracking with Integral Action .....	75
2.6	Output-Based Hyperplane Design .....	77
2.6.1	Static Output-Feedback Hyperplane Design .....	78
2.6.2	Static Output-Feedback Control Law Development.....	83
2.6.3	Dynamic Output-Feedback Hyperplane Design .....	85
2.6.4	Dynamic Output-Feedback Control Law Development ....	87
2.6.5	Case Study: Vehicle Stability in a Split-Mu Maneuver ....	88
2.7	Integral Sliding Mode Control .....	89
2.7.1	Problem Formulation .....	90
2.7.2	Control Design Objective.....	91
2.7.3	Linear Case.....	91
2.7.4	ISM Compensation of Unmatched Disturbances .....	94
2.8	Notes and References.....	96
2.9	Exercises .....	99
<b>3</b>	<b>Conventional Sliding Mode Observers .....</b>	<b>105</b>
3.1	Introduction .....	105
3.2	A Simple Sliding Mode Observer .....	106
3.3	Robustness Properties of Sliding Mode Observers .....	111
3.4	A Generic Conventional Sliding Mode Observer .....	121
3.5	A Sliding Mode Observer for Nonlinear Systems .....	128
3.6	Fault Detection: A Simulation Example .....	133
3.7	Notes and References.....	136
3.8	Exercises .....	137
<b>4</b>	<b>Second-Order Sliding Mode Controllers and Differentiators.....</b>	<b>143</b>
4.1	Introduction .....	143
4.2	2-Sliding Mode Controllers .....	147
4.2.1	Twisting Controller .....	148
4.2.2	Suboptimal Algorithm .....	151
4.2.3	Control Algorithm with Prescribed Convergence Law .....	152
4.2.4	Quasi-Continuous Control Algorithm .....	153
4.2.5	Accuracy of 2-Sliding Mode Controllers .....	155
4.3	Control of Relative Degree One Systems.....	155
4.3.1	Super-Twisting Controller .....	155
4.3.2	First-Order Differentiator .....	159
4.4	Differentiator-Based Output-Feedback 2-SM Control .....	161
4.5	Chattering Attenuation .....	163
4.6	Case Study: Pendulum Control .....	166
4.6.1	Discontinuous Control .....	167
4.6.2	Chattering Attenuation.....	169

4.7	Variable-Gain Super-Twisting Control .....	170
4.7.1	Problem Statement .....	171
4.7.2	The Variable-Gain Super-Twisting Algorithm .....	172
4.8	Case Study: The Mass–Spring–Damper System .....	176
4.8.1	Model Description .....	176
4.8.2	Problem Statement .....	177
4.8.3	Control Design .....	178
4.8.4	Experimental Results .....	179
4.9	Notes and References .....	179
4.10	Exercises .....	182
<b>5</b>	<b>Analysis of Sliding Mode Controllers in the Frequency Domain .....</b>	<b>183</b>
5.1	Introduction .....	183
5.2	Conventional SMC Algorithm: DF Analysis .....	184
5.3	Twisting Algorithm: DF Analysis .....	193
5.4	Super-Twisting Algorithm: DF Analysis .....	196
5.4.1	DF of Super-Twisting Algorithm .....	196
5.4.2	Existence of the Periodic Solutions .....	198
5.4.3	Stability of Periodic Solution .....	200
5.5	Prescribed Convergence Control Law: DF Analysis .....	201
5.6	Suboptimal Algorithm: DF Analysis .....	203
5.7	Comparisons of 2-Sliding Mode Control Algorithms .....	205
5.8	Notes and References .....	208
5.9	Exercises .....	208
<b>6</b>	<b>Higher-Order Sliding Mode Controllers and Differentiators .....</b>	<b>213</b>
6.1	Introduction .....	214
6.2	Single-Input Single-Output Regulation Problem .....	216
6.3	Homogeneity, Finite-Time Stability, and Accuracy .....	217
6.4	Homogeneous Sliding Modes .....	222
6.5	Accuracy of Homogeneous 2-Sliding Modes .....	223
6.6	Arbitrary-Order Sliding Mode Controllers .....	225
6.6.1	Nested Sliding Controllers .....	225
6.6.2	Quasi-continuous Sliding Controllers .....	227
6.7	Arbitrary-Order Robust Exact Differentiation .....	228
6.8	Output-Feedback Control .....	230
6.9	Tuning of the Controllers .....	233
6.9.1	Control Magnitude Tuning .....	233
6.9.2	Parametric Tuning .....	233
6.10	Case Study: Car Steering Control .....	234
6.11	Case Study: Blood Glucose Regulation .....	237
6.11.1	Introduction to Diabetes .....	237
6.11.2	Insulin–Glucose Regulation Dynamical Model .....	240
6.11.3	Higher-Order Sliding Mode Controller Design .....	241
6.11.4	Simulation .....	244

6.12	Notes and References .....	247
6.13	Exercises .....	248
<b>7</b>	<b>Observation and Identification via HOSM Observers .....</b>	<b>251</b>
7.1	Observation/Identification of Mechanical Systems .....	252
7.1.1	Super-Twisting Observer .....	253
7.1.2	Equivalent Output Injection Analysis .....	255
7.1.3	Parameter Identification .....	259
7.2	Observation in Single-Output Linear Systems .....	265
7.2.1	Non-perturbed Case .....	265
7.2.2	Perturbed Case .....	266
7.2.3	Design of the Observer for Strongly Observable Systems .....	268
7.3	Observers for Single-Output Nonlinear Systems.....	274
7.3.1	Differentiator-Based Observer .....	275
7.3.2	Disturbance Identification .....	278
7.4	Regulation and Tracking Controllers Driven by SM Observers ....	280
7.4.1	Motivation .....	280
7.4.2	Problem Statement .....	281
7.4.3	Theoretically Exact Output-Feedback Stabilization (EOFS) .....	282
7.4.4	Output Integral Sliding Mode Control .....	283
7.4.5	Precision of the Observation and Identification Processes .....	284
7.5	Notes and References.....	286
7.6	Exercises .....	286
<b>8</b>	<b>Disturbance Observer Based Control: Aerospace Applications .....</b>	<b>291</b>
8.1	Problem Formulation .....	291
8.1.1	Asymptotic Compensated Dynamics .....	292
8.1.2	Finite-Time-Convergent Compensated Dynamics.....	293
8.1.3	Sliding Variable Disturbed Dynamics.....	294
8.1.4	Output Tracking Error Disturbed Dynamics.....	294
8.2	Perturbation Term Reconstruction via a Disturbance Observer ....	295
8.2.1	SMDO Based on Conventional SMC .....	295
8.2.2	SMDO Based on Super-Twisting Control .....	296
8.2.3	Design of the SMC Driven by the SMDO .....	297
8.3	Case Study: Reusable Launch Vehicle Control .....	298
8.3.1	Mathematical Model of Reusable Launch Vehicle .....	298
8.3.2	Reusable Launch Vehicle Control Problem Formulation ..	300
8.3.3	Multiple-Loop Asymptotic SMC/SMDO Design .....	301
8.3.4	Flight Simulation Results and Analysis.....	305

8.4	Case Study: Satellite Formation Control .....	309
8.4.1	Satellite Formation Mathematical Model .....	310
8.4.2	Satellite Formation Control in SMC/SMDO .....	313
8.5	Simulation Study .....	314
8.6	Notes and References .....	316
8.7	Exercises .....	318
<b>A</b>	<b>Mathematical Preliminaries .....</b>	<b>321</b>
A.1	Linear Algebra .....	321
A.1.1	Rank and Determinant .....	321
A.1.2	Eigenvalues and Eigenvectors .....	322
A.1.3	QR Decomposition.....	323
A.1.4	Norms.....	323
A.1.5	Quadratic Forms .....	324
<b>B</b>	<b>Describing Functions .....</b>	<b>327</b>
B.1	Describing Function Fundamentals .....	327
B.1.1	Low-Pass Filter Hypothesis and Describing Function .....	328
B.1.2	Limit Cycle Analysis Using Describing Functions.....	328
B.1.3	Stability Analysis of the Limit Cycle .....	329
<b>C</b>	<b>Linear Systems Theory .....</b>	<b>331</b>
C.1	Introduction .....	331
C.1.1	Linear Time-Invariant Systems.....	331
C.1.2	Controllability and Observability .....	332
C.1.3	Invariant Zeros .....	333
C.1.4	State Feedback Control .....	334
C.1.5	Static Output Feedback Control .....	335
<b>D</b>	<b>Lyapunov Stability .....</b>	<b>337</b>
D.1	Local Results.....	338
D.2	Global Results .....	338
D.2.1	Quadratic Stability .....	339
	<b>Bibliography .....</b>	<b>343</b>
	<b>Index .....</b>	<b>353</b>

Sliding Mode Control and Observation

Shtessel, Y.; Edwards, C.; Fridman, L.; Levant, A.

2014, XVII, 356 p. 168 illus., Hardcover

ISBN: 978-0-8176-4892-3

A product of Birkhäuser Basel