

Variable Structure Systems: from Principles to Implementation

**Edited by Asif Sabanovic, Leonid Fridman
and Sarah Spurgeon**

The Institution of Electrical Engineers

Contents

Contributors	xiii
Preface	xvii
Part I Sliding mode control theory	1
1 Sliding mode control	3
<i>Vadim I. Utkin</i>	
1.1 Introduction	3
1.2 The concept of a ‘sliding mode’	3
1.3 Sliding mode equations	7
1.4 Existence conditions	9
1.5 Design principles	11
1.6 Discrete-time sliding mode control	13
1.7 Chattering problem	14
1.8 Sliding mode observers	15
1.9 Conclusion	16
1.10 Further Reading	17
2 Sliding mode regulator design	19
<i>Vadim I. Utkin, Alexander G. Loukianov, B. Castillo-Toledo and J. Rivera</i>	
2.1 Introduction	19
2.2 Error feedback sliding mode control problem	22
2.3 Discontinuous dynamic regulator for multivariable linear systems	22
2.3.1 Solvability conditions	22
2.3.2 Sliding regulator for linear systems in Regular form	25
2.3.3 Block Controllable form with disturbances	27
2.4 Discontinuous dynamic regulator for nonlinear systems	31
2.4.1 Solvability conditions	31

2.4.2	Sliding regulator for nonlinear systems in Regular form	34
2.4.3	Nonlinear Block Controllable form with disturbances	37
2.5	Conclusions	42
2.6	Acknowledgement	42
2.7	References	42
3	Deterministic output noise effects in sliding mode observation	45
<i>Alex S. Poznyak</i>		
3.1	Preliminaries	45
3.2	State-estimation as a component of identification theory: a short survey	46
3.2.1	Parameter estimation	46
3.2.2	State-estimation	46
3.2.3	Simultaneous state and parameter estimation	47
3.2.4	Observations under uncertainties	48
3.2.5	Sliding mode observation	48
3.3	Estimation problem statement: formalism	49
3.3.1	The consistent class of nonlinear systems	49
3.3.2	The extended system and problem formulation	49
3.4	The nominal (nondisturbed) system and observability property	50
3.4.1	Nondisturbed system	50
3.4.2	Output differentiation as a generator of new outputs	51
3.4.3	Observability matrix	52
3.5	Examples of observability analysis	53
3.5.1	Simple pendulum	53
3.5.2	Duffing equation	55
3.5.3	Van der Pol oscillator	56
3.6	Observer structure	58
3.6.1	Asymptotic nonlinear observers	58
3.6.2	Output noise	59
3.7	Standard high-gain observer	60
3.7.1	A specific class of dynamic models	60
3.7.2	Mechanical example	60
3.7.3	High-gain observer structure	61
3.7.4	Upper bound for estimation error and asymptotic consistency property	61
3.7.5	Analysis of the matrix Riccati equation	64
3.7.6	Noise generated by stable filters	66
3.8	Sliding mode observers	66
3.8.1	Structure of sliding mode observers	66
3.8.2	Fundamental properties	67

3.8.3	Bounded output-noise	70
3.8.4	Output noise formed by a stable filter	73
3.9	Conclusion	75
3.10	Appendix	75
3.11	References	78
4	Stochastic output noise effects in sliding mode observation	81
<i>Alex S. Poznyak</i>		
4.1	Introduction	81
4.2	Problem setting	82
4.2.1	Stochastic continuous-time system	82
4.2.2	Noise properties	85
4.2.3	Observer structures	86
4.2.4	Problem formulation	87
4.3	Main result	87
4.3.1	Convergence analysis for the first observer scheme	87
4.3.2	Convergence analysis for the second observer scheme	92
4.4	Convergence zone analysis	94
4.5	Conclusion	96
4.6	References	96
5	Discrete-time VSS	99
<i>Čedomir Milosavljević</i>		
5.1	Discrete-time variable structure control (DVSC)	99
5.2	Control for discrete-time systems (review of early works)	102
5.3	Definition of sliding mode and quasi-sliding modes in discrete-time	104
5.4	Lyapunov stability and invariant sets in discrete-time systems	105
5.5	'Sliding conditions' in discrete-time	106
5.6	DVSC with attractive boundary layer	107
5.7	DVSC with disturbance estimation	110
5.8	DVSC with sliding sectors	112
5.9	Properties of DVSC	114
5.10	Approaches to design the 'sliding surface' in discrete-time	115
5.11	Numerical examples	117
5.12	Issues in the realisation of DT SMC	121
5.13	References	124
Part II New trends in sliding mode control		129
6	Robustness issues of 2-sliding mode control	131
<i>Arie Levant and Leonid Fridman</i>		
6.1	Introduction	131
6.2	Main notions and the problem statement	132
6.2.1	Definitions	132

6.2.2	2-sliding control problem	133
6.3	Standard 2-sliding controllers in systems with relative degree 2	135
6.4	Sampling noise and variable sampling step	140
6.5	Robust exact differentiation	141
6.6	Robust output-feedback control: differentiator in the feedback	143
6.7	Output feedback: simulation results	144
6.8	Influence of the actuator dynamics	146
6.8.1	Instability of r -sliding modes, $r > 2$, generated by the twisting controller	146
6.8.2	High relative-degree systems with fast actuators	147
6.8.3	Frequency domain analysis of chattering in 2-sliding mode systems with actuators	148
6.9	Conclusions	151
6.10	References	153
7	Sliding modes, delta-modulation and output feedback control of dynamic systems	157
	<i>Hebertt Sira-Ramírez and Luis Iván Lugo Villeda</i>	
7.1	Introduction	157
7.2	Delta-modulators and sliding modes	158
7.2.1	The equivalent control method in time differentiation of signals	159
7.2.2	An illustrative example with experimental results	161
7.3	Output feedback control of differentially flat systems	163
7.3.1	A third order integrator system	165
7.3.2	Flatness based control of the synchronous generator	167
7.3.3	The non-holonomic car	170
7.4	Delta modulation and higher order sliding mode differentiation	172
7.5	References	175
8	Analysis of sliding modes in the frequency domain	177
	<i>Igor Boiko</i>	
8.1	Introduction	177
8.2	Introduction to the locus of a perturbed relay system (LPRS)	179
8.3	Computation of the LPRS for a non-integrating plant	183
8.3.1	Matrix state space description approach	183
8.3.2	Partial fraction expansion technique	185
8.3.3	Transfer function description approach	185
8.4	Computation of the LPRS for an integrating plant	187
8.4.1	Matrix state space description approach	187
8.4.2	Transfer function description approach	190
8.5	Frequency domain conditions of sliding mode existence	191
8.6	Example of chattering and disturbance attenuation analysis	193

8.7	Conclusion	195
8.8	References	195
9	Output tracking in causal nonminimum-phase systems using sliding modes	197
<i>Yuri B. Shtessel and Ilya A. Shkolnikov</i>		
9.1	Introduction	197
9.2	Motivational example: consideration of a nonminimum-phase plant	198
9.2.1	Aircraft flight path angle tracking in the pitch plane	198
9.2.2	The normal form and the inverse dynamics of a nonminimum-phase plant: the feedforward/feedback control approach	201
9.2.3	Asymptotic output tracking problem: the state-feedback approach	202
9.2.4	Conclusions	203
9.3	Stable system centre design for feedforward/feedback tracking control for systems in a normal canonical form	204
9.3.1	Problem formulation	204
9.3.2	Replacing output-tracking by state-tracking	204
9.3.3	Stable system centre design (a method to obtain the IID asymptotically)	207
9.3.4	Conclusion	208
9.4	Asymptotic output tracking by state-feedback: dynamic sliding manifold technique	209
9.4.1	Dynamic sliding manifold (DSM) of full order	209
9.4.2	Dynamic sliding manifold of reduced order	210
9.4.3	Case study: The flight path angle tracking in a pitch plane of F-16 jet fighter	212
9.5	Conclusions	214
9.6	References	216
10	Sliding mode control and chaos	219
<i>Xinghuo Yu and Guanrong Chen</i>		
10.1	Introduction	219
10.2	Discretisation chaos in SMC	220
10.2.1	Discretisation of an equivalent control based SMC system	221
10.2.2	Discretisation behaviours analysis	223
10.2.3	An example	226
10.3	Time-delayed chaos control with SMC	229
10.3.1	Time-delayed feedback control based on SMC	230
10.3.2	Estimation of the delay time τ	234
10.3.3	An example	234
10.4	Generalising the OGY method using SMC	236

10.4.1	SMC-based OGY method for MIMO systems	237
10.4.2	An example	239
10.5	Conclusions	241
10.6	References	241
Part III Applications of sliding mode control		243
11 Sliding modes in fuzzy and neural network systems		245
<i>Kemalettin Erbatur, Yildiray Yildiz and Asif Sabanovic</i>		
11.1	Introduction	245
11.2	Sliding mode control and intelligence	245
11.2.1	Sliding mode control design	246
11.2.2	Intelligence in action	246
11.3	A sliding mode neuro-controller	253
11.3.1	Finding the weight updates	254
11.3.2	Disturbance rejection	255
11.3.3	Stability and robustness analysis	256
11.3.4	Simulation results	257
11.4	Conclusion	261
11.5	References	262
12 SMC applications in power electronics		265
<i>Domingo Biel Solé and Enric Fossas Colet</i>		
12.1	DC-DC power conversion	265
12.1.1	Electrical and state-space models	265
12.1.2	Sliding mode control analysis and design	267
12.2	DC-AC power conversion	269
12.2.1	Full-bridge power converter	270
12.2.2	Tracking signal sliding mode control	270
12.3	AC-DC power conversion	272
12.3.1	Rectifier power converter	273
12.3.2	Control objectives	274
12.3.3	Ideal sliding dynamics	274
12.3.4	Control design	275
12.4	Control implementation	276
12.4.1	Sliding mode control implementation in switching converters	277
12.4.2	Comparative study of the implementation methods	280
12.4.3	Analogue electronic implementation	283
12.4.4	Digital electronic implementations	287
12.5	Example: a ZAD inverter	287
12.6	References	292
13 Sliding modes in motion control systems		295
<i>Asif Sabanovic and Karel Jezernik</i>		
13.1	Introduction	295

13.2	SMC in motion control system	296
13.2.1	Control problem formulation	296
13.2.2	Selection of control input	297
13.2.3	Sliding mode disturbance observer	299
13.3	Timing-belt servosystem	301
13.3.1	Experimental verification	302
13.3.2	Belt stretch control	304
13.4	Control and state observers for induction machine	308
13.5	Induction machine flux and velocity observer	314
13.6	Conclusions	317
13.7	References	317
14	Sliding mode control for automobile applications	319
<i>Vadim I. Utkin and Hao-Chi Chang</i>		
14.1	Introduction	319
14.2	Estimator for automotive alternator	320
14.3	Estimation of fuelling rate and AFR using UEGO	321
14.4	NO _x control for EGR-VGT diesel engine	324
14.5	ABS control using sliding mode optimisation	328
14.6	Conclusions	331
14.7	References	331
15	The application of sliding mode control algorithms to a diesel generator set	333
<i>Keng Boon Goh, Sarah K. Spurgeon and N. Barrie Jones</i>		
15.1	Introduction	333
15.2	Sliding mode integral tracking (SMIT) control system	334
15.3	Sliding mode model-following (SMMF) control system	337
15.4	Second order sliding mode (SOSM) control system	340
15.5	Diesel generator system	341
15.6	Control systems setting and simulation	342
15.7	Control systems implementation results	344
15.8	Conclusion	350
15.9	References	350
16	Motion control of underwater objects by using second order sliding mode techniques	353
<i>Giorgio Bartolini, Alessandro Pisano, Elisabetta Punta and Elio Usai</i>		
16.1	Introduction	353
16.2	Nonlinear output-feedback control via 2-SM controllers and 2-SM differentiators	354
16.3	A multi-input version of the control problem	357
16.4	Mathematical model	359
16.4.1	Vehicle dynamics in the B-frame	360
16.4.2	Thruster dynamics	360

16.4.3	The position and attitude control	361
16.4.4	Simulation example	362
16.5	Test results: motion control for an underwater vehicle prototype	363
16.5.1	The UV model	366
16.5.2	Controller design	367
16.5.3	The experimental setup: implementation issues and test results	370
16.6	Conclusions	374
16.7	References	374
17	Semiglobal stabilisation of linear uncertain system via delayed relay control	377
<i>Leonid Fridman, Vadim Strygin and Andrei Polyakov</i>		
17.1	Introduction	377
17.1.1	Oscillatory nature of relay delayed systems	378
17.1.2	Problem formulation	380
17.2	Two simple cases	381
17.2.1	Scalar system	381
17.2.2	System stability	384
17.2.3	Stabilisation of a second order system with unstable complex conjugate eigenvalues	385
17.3	Generalisation of the control algorithm for MIMO systems	386
17.4	Semiglobal stabilisation of a mechanical system via relay delayed control	387
17.4.1	Stabilisation of linearised mechanical systems via relay delayed control	387
17.4.2	Generalisation of control algorithm to the case of nonlinear mechanical system	389
17.5	Numerical examples	391
17.5.1	Stabilisation of inverted pendulum	391
17.5.2	Double inverted pendulum	391
17.6	Appendix	394
17.6.1	Staying in the neighbourhood	394
17.6.2	Existence of arbitrary small values of solution	396
17.6.3	Proof of Theorem 1	397
17.7	References	399
Index		401