

Contents

Preface	vii
Literature Recommendations	ix
Acknowledgements	ix
1 Fundamentals of Nonlinear Systems	1
1.1 System Description and System Behavior	1
1.1.1 Linear and Nonlinear Systems.....	1
1.1.2 System Description and Nonlinear Control Loops	2
1.1.3 Equilibrium Points of Nonlinear Systems	5
1.1.4 Example: Satellite	7
1.1.5 Equilibrium Points of Linear Systems	9
1.1.6 Stability and Asymptotic Stability	11
1.1.7 Exponential Stability of Equilibrium Points	18
1.1.8 Instability of Equilibrium Points	20
1.1.9 Stability in the Case of Variable Input Signals	25
1.1.10 Limit Cycles	28
1.1.11 Sliding Modes.....	30
1.1.12 Chaos.....	33
1.1.13 Discrete-Time Systems	35
1.2 Solution of Nonlinear Differential Equations	37
1.2.1 Existence of Solutions.....	37
1.2.2 Numerical Solution and Euler Method	41
1.2.3 Accuracy of the Numerical Solution.....	43
1.2.4 The Modified Euler Method	44

1.2.5	The Heun and Simpson Methods	45
1.2.6	The Runge-Kutta Methods	47
1.2.7	Adaptation of the Step Size	49
1.2.8	The Adams-Bashforth Methods	51
1.2.9	The Adams-Moulton Predictor-Corrector Methods	52
1.2.10	Stability of Numerical Integration Methods	53
1.2.11	Stiff Systems and Their Solutions	56
1.3	Exercises	58
2	Limit Cycles and Stability Criteria	69
2.1	The Describing Function Method	69
2.1.1	Idea behind the Method	69
2.1.2	Illustrative Example	73
2.1.3	Characteristic Curves and Their Describing Functions	75
2.1.4	Stability Analysis of Limit Cycles	82
2.1.5	Example: Power-Assisted Steering System	85
2.2	Absolute Stability	89
2.2.1	The Concept of Absolute Stability	89
2.2.2	The Popov Criterion and Its Application	91
2.2.3	The Aizerman and Kalman Conjectures	97
2.2.4	Example: Controlling a Ship	99
2.2.5	The Circle Criterion	103
2.2.6	The Tsytkin Criterion for Discrete-Time Systems	110
2.3	Lyapunov's Stability Theory	113
2.3.1	The Concept and the Direct Method	113
2.3.2	Illustrative Example	118
2.3.3	Quadratic Lyapunov Functions	119
2.3.4	Example: Mutualism	121
2.3.5	The Direct Method for Discrete-Time Systems	125
2.3.6	The Indirect Method	126
2.3.7	Determining Exponential Stability	127
2.3.8	Example: Underwater Glider	129
2.3.9	Catchment Regions	134
2.3.10	LaSalle's Invariance Principle	137
2.3.11	Instability Criterion	142
2.4	Passivity and Stability	143
2.4.1	Passive Systems	143
2.4.2	Stability of Passive Systems	146
2.4.3	Passivity of Connected Systems	148
2.4.4	Passivity of Linear Systems	151
2.4.5	Example: Transporting System for Material Webs	155
2.4.6	Positive Real Transfer Functions	158
2.4.7	Equivalence of Positive Realness and Passivity	163
2.4.8	Lossless Hamiltonian Systems	168
2.4.9	Example: Self-Balancing Vehicle	175

2.4.10	Dissipative Hamiltonian Systems	179
2.4.11	Example: Separately Excited Direct-Current Machine	182
2.4.12	Linear Hamiltonian Systems	185
2.5	Exercises	193
3	Controllability and Flatness	205
3.1	Controllability	205
3.1.1	Definition of Controllability	205
3.1.2	Global and Local Controllability	212
3.1.3	Proving Controllability	215
3.1.4	Example: Industrial Robot	219
3.1.5	Small-Time Local Controllability of Driftless Systems	224
3.1.6	Example: Motor Vehicle with Trailer	231
3.1.7	Omnidirectional Controllability	233
3.1.8	Example: Steam Generator	236
3.2	Flatness	239
3.2.1	Basic Concept and Definition of Flatness	239
3.2.2	The Lie-Bäcklund Transformation	243
3.2.3	Example: VTOL Aircraft	246
3.2.4	Flatness and Controllability	250
3.2.5	Flat Outputs of Linear Systems	251
3.2.6	Verification of Flatness	255
3.3	Nonlinear State Transformations	259
3.3.1	Transformations and Transformed System Equations	259
3.3.2	Illustrative Example	264
3.3.3	Example: Park Transformation	266
3.3.4	Determining the Transformation Rule	273
3.3.5	Illustration Using Linear Systems	274
3.4	Exercises	277
4	Nonlinear Control of Linear Systems	285
4.1	Control with Anti-Windup	285
4.1.1	The Windup Effect	285
4.1.2	PID Controller with Anti-Windup Element	287
4.1.3	Example: Direct-Current Motor	288
4.1.4	A General Anti-Windup Method	291
4.1.5	Dimensioning the General Anti-Windup Controller	295
4.1.6	Stability	298
4.2	Time-Optimal Control	299
4.2.1	Fundamentals and Fel'dbaum's Theorem	299
4.2.2	Computation of Time-Optimal Controls	301
4.2.3	Example $1/s^2$	303
4.2.4	Time-Optimal Control of Low-Order Systems	307
4.2.5	Example: Submarine	309
4.2.6	Time-Optimal Pilot Control	313

4.3	Variable Structure Control Without Sliding Mode	314
4.3.1	Fundamentals of Variable Structure Control	314
4.3.2	Piecewise Linear Control	318
4.3.3	Example: Ship-to-Shore Gantry Crane	322
4.4	Saturation Controllers	327
4.4.1	Basics and Stability	327
4.4.2	Design in Multiple Steps	331
4.4.3	Example: Helicopter	332
4.5	Exercises	335
5	Nonlinear Control of Nonlinear Systems	345
5.1	Gain-Scheduling Control	345
5.1.1	Mode of Operation and Design	345
5.1.2	Illustrative Example	351
5.1.3	Example: Solar Power Plant	354
5.2	Input-Output Linearization	359
5.2.1	Basic Concept and Nonlinear Controller Canonical Form	359
5.2.2	Nonlinear Controller and Linear Control Loop	364
5.2.3	Example: Magnetic Bearing	367
5.2.4	Plants with Internal Dynamics	372
5.2.5	Design Procedure	378
5.2.6	Example: Lunar Module	379
5.2.7	Input-Output Linearization of General SISO Systems ..	384
5.2.8	Relative Degree and Internal Dynamics of Linear Systems	389
5.2.9	Control Law for the Linear Case	395
5.2.10	Stability of Internal and Zero Dynamics	398
5.2.11	Input-Output Linearization of MIMO Systems	401
5.2.12	MIMO Control Loops in State-Space Representation ..	405
5.2.13	Example: Combustion Engine	410
5.3	Full-State Linearization	413
5.3.1	Full-State Linearization of SISO Systems	413
5.3.2	Example: Drilling Rig	419
5.3.3	Full-State Linearization of MIMO Systems	426
5.3.4	Flatness of Full-State Linearizable Systems	430
5.3.5	Example: Rocket	432
5.4	Feedforward and Feedback Control of Flat Systems	435
5.4.1	Fundamentals	435
5.4.2	Feedforward Controls Using Fictitious Flat Outputs ..	437
5.4.3	Flatness-Based Feedforward Control of Linear Systems ..	441
5.4.4	Example: Propulsion-Based Aircraft Control	443
5.4.5	Flatness-Based Feedback Control of Nonlinear Systems ..	448
5.4.6	Example: Pneumatic Motor	453
5.4.7	Flat Inputs and Their Design	458
5.4.8	Flat Inputs of Linear Systems	462

5.4.9	Example: Economic Market Model.....	463
5.5	Control Lyapunov Functions	465
5.5.1	Fundamentals	465
5.5.2	Control Lyapunov Functions for Linear Systems	467
5.5.3	Control Lyapunov Functions for Control-Affine Systems	468
5.5.4	Illustrative Example	470
5.5.5	Example: Power Plant with Grid Feed-In	472
5.6	The Backstepping Method	478
5.6.1	Fundamentals	478
5.6.2	Recursive Scheme for the Controller Design	483
5.6.3	Illustrative Examples	485
5.6.4	Example: Fluid System with Chaotic Behavior	489
5.7	Exercises	493
6	Nonlinear Control of Linear and Nonlinear Systems	505
6.1	Model-Based Predictive Control	505
6.1.1	Basics and Functionality	505
6.1.2	Linear Model Predictive Control without Constraints ..	509
6.1.3	LMPC with Constraints	513
6.1.4	Example: Drainage System	516
6.1.5	Nonlinear Model Predictive Control.....	521
6.1.6	Example: Evaporation Plant	526
6.2	Variable Structure Control with Sliding Mode	530
6.2.1	Basics and Characteristics	530
6.2.2	Design for Linear Plants.....	532
6.2.3	Dynamics in the Sliding Mode	534
6.2.4	Verification of Robustness	535
6.2.5	Example: DC-to-DC Converter	536
6.2.6	Design for Nonlinear Plants.....	542
6.2.7	Example: Optical Switch	544
6.3	Passivity-Based Control	547
6.3.1	Control of Passive Systems Using Static Controllers....	547
6.3.2	Example: Damping of Seismic Building Vibrations....	550
6.3.3	Passivation of Non-Passive Linear Systems.....	558
6.3.4	Passivation of Non-Passive Control-Affine Systems....	563
6.3.5	Passivity-Based Control with IDA	565
6.3.6	Example: Paper Machine	570
6.4	Fuzzy Control	574
6.4.1	Introduction	574
6.4.2	Fuzzification	575
6.4.3	Inference	577
6.4.4	Defuzzification	584
6.4.5	Fuzzy Systems and Fuzzy Controllers	585
6.4.6	Example: Distance Control for Automobiles.....	588
6.5	Exercises	593

7	Observers for Nonlinear Systems	603
7.1	Observability of Nonlinear Systems	603
7.1.1	Definition of Observability	603
7.1.2	Observability of Autonomous Systems	607
7.1.3	Example: Synchronous Generator	610
7.1.4	Observability of General Nonlinear Systems	612
7.1.5	Nonlinear Observability Canonical Form	614
7.1.6	Observability of Control-Affine Systems	617
7.2	Canonical Forms and the Canonical Form Observer	620
7.3	Luenberger Observers for Nonlinear Control Loops	624
7.4	Observer Design Using Linearization	626
7.4.1	Basics and Design	626
7.4.2	Control Loop with Observer	630
7.4.3	Example: Bioreactor	631
7.5	The Extended Kalman Filter	635
7.5.1	Kalman Filter for Linear Systems	635
7.5.2	The EKF for Nonlinear Systems	637
7.5.3	Example: Jet Engine	640
7.6	High-Gain Observer	643
7.6.1	Concept and Design	643
7.6.2	High-Gain Observers in General Form	649
7.6.3	Example: Chemical Reactor	651
7.6.4	The Case of Control-Affine Systems	655
7.7	Exercises	659
8	Solutions to the Exercises	663
A	Appendix	695
A.1	Proof of the General Circle Criterion	695
A.2	Parameters of the Container Crane Control	699
B	List of Symbols	701
	References	707
	Index	733