

Contents

<i>Preface</i>	<i>page ix</i>
Part I Core Material	
1 Historical Introduction	1
1.1 Historical Overview	3
1.2 Lessons from History	4
1.3 Control and Information	12
1.4 Notes and References	21
2 Dynamical Systems	21
2.1 Introduction: The Pendulum as a Dynamical System	24
2.2 General Formulation	25
2.3 Frequency Domain	28
2.4 Time Domain	36
2.5 Stability	46
2.6 Bifurcations	52
2.7 Summary	58
2.8 Notes and References	60
Problems	61
	62
3 Frequency-Domain Control	67
3.1 Basic Feedback Ideas	68
3.2 Two Case Studies	75
3.3 Integral, Derivative, and PID	78
3.4 Feedforward	83
3.5 Stability of Closed-Loop Systems	88
3.6 Delays and Nonminimum Phase	92
3.7 Designing the Control	100
3.8 MIMO Systems	110
3.9 Summary	121
3.10 Notes and References	121
Problems	122
4 Time-Domain Control	129
4.1 Controllability and Observability	130

4.2	Control Based on the State	142
4.3	Control Based (Indirectly) on the Output	148
4.4	Summary	156
4.5	Notes and References	157
	Problems	157
5	Discrete-Time Systems	161
5.1	Discretizing Signals	163
5.2	Tools for Discrete Dynamical Systems	175
5.3	Discretizing Dynamical Systems	181
5.4	Design of Digital Controllers	186
5.5	Summary	196
5.6	Notes and References	197
	Problems	198
6	System Identification	205
6.1	Physics or Phenomenology?	206
6.2	Measuring Dynamics	207
6.3	Model Building	222
6.4	Model Selection	227
6.5	Model Reduction	233
6.6	Summary	236
6.7	Notes and References	237
	Problems	238
	Part II Advanced Ideas	249
7	Optimal Control	251
7.1	One-Dimensional Example	252
7.2	Continuous Systems	254
7.3	Linear Quadratic Regulator	259
7.4	Dynamic Programming	263
7.5	Hard Constraints	269
7.6	Feedback	276
7.7	Numerical Methods	286
7.8	Summary	288
7.9	Notes and References	289
	Problems	291
8	Stochastic Systems	297
8.1	Kalman Filter	298
8.2	Linear Quadratic Gaussian Control	313
8.3	Bayesian Filtering	319
8.4	Nonlinear Filtering	326
8.5	Why State Estimation Can Be a Hard Problem	340

Contents

vii

8.6	Stochastic Optimal Control	345
8.7	Smoothing and Prediction	348
8.8	Summary	352
8.9	Notes and References	352
	Problems	355
9	Robust Control	363
9.1	Robust Feedforward	365
9.2	Robust Feedback	371
9.3	Risk	376
9.4	Worst-Case Methods: The \mathcal{H}_∞ Min-Max Approach	386
9.5	Summary	395
9.6	Notes and References	398
	Problems	399
10	Adaptive Control	404
10.1	Direct Methods	407
10.2	Indirect Methods	413
10.3	Adaptive Feedforward Control	424
10.4	Optimal Adaptive Control	430
10.5	Neural Networks	437
10.6	Summary	443
10.7	Notes and References	444
	Problems	446
11	Nonlinear Control	454
11.1	Feedback Linearization	455
11.2	Lyapunov-Based Design	466
11.3	Collective Dynamics	469
11.4	Controlling Chaos	476
11.5	Summary	480
11.6	Notes and References	480
	Problems	481
	Part III Special Topics	491
12	Discrete-State Systems	493
12.1	Discrete-State Models	493
12.2	Inferring States and Models	500
12.3	Control	508
12.4	Summary	511
12.5	Notes and References	512
	Problems	513
13	Quantum Control	516
13.1	Quantum Mechanics	517

13.2 Three Types of Quantum Control	520
13.3 Physical Example	523
13.4 How Different Is Quantum Control?	526
13.5 Summary	528
13.6 Notes and References	530
Problems	531
14 Networks and Complex Systems	533
14.1 Networks in a Nutshell	535
14.2 From Dynamics to Graphs to Networks	540
14.3 Structural Controllability	541
14.4 Minimum Inputs Problem	543
14.5 Control Effort	546
14.6 Complex Systems	551
14.7 Summary	554
14.8 Notes and References	555
Problems	557
15 Limits to Control	561
15.1 Causal Limits	561
15.2 Information-Theoretic Limits	574
15.3 Thermodynamic Limits	588
15.4 Summary	608
15.5 Notes and References	610
Problems	613
<i>References</i>	619
<i>Index</i>	641