CONTENTS

CONTENTS OVERVIEW vii

ACKNOWLEDGEMENTS xxi

PREFACE xxiii

I THE ELEMENTS 1

PREVIEW 3

1 THE EXCITEMENT OF CONTROL ENGINEERING 5
- 1.1 Preview 5
- 1.2 Motivation for Control Engineering 5
- 1.3 Historical Periods of Control Theory 9
- 1.4 Types of Control-System Design 10
- 1.5 System Integration 11
- 1.6 Summary 18
- 1.7 Further Reading 19

2 INTRODUCTION TO THE PRINCIPLES OF FEEDBACK 21
- 2.1 Preview 21
- 2.2 The Principal Goal of Control 21
- 2.3 A Motivating Industrial Example 22
- 2.4 Definition of the Problem 27
- 2.5 Prototype Solution to the Control Problem via Inversion 29
- 2.6 High-Gain Feedback and Inversion 32
- 2.7 From Open- to Closed-Loop Architectures 34

2.8 Trade-offs Involved in Choosing the Feedback Gain 36
2.9 Measurements 36
2.10 Summary 38
2.11 Further Reading 39

3 MODELING 41
3.1 Preview 41
3.2 The ***Raison d'être*** for Models 41
3.3 Model Complexity 42
3.4 Building Models 44
3.5 Model Structures 45
3.6 State Space Models 45
3.7 Solution of Continuous-Time State Space Models 49
3.8 High-Order Differential and Difference-Equation Models 50
3.9 Modeling Errors 50
3.10 Linearization 52
3.11 Case Studies 57
3.12 Summary 58
3.13 Further Reading 60
3.14 Problems for the Reader 61

4 CONTINUOUS-TIME SIGNALS AND SYSTEMS 65
4.1 Preview 65
4.2 Linear Continuous-Time Models 65
4.3 Laplace Transforms 66
4.4 Laplace Transform. Properties and Examples 67
4.5 Transfer Functions 70
4.6 Stability of Transfer Functions 74
4.7 Impulse and Step Responses of Continuous-Time Linear Systems 74
4.8 Poles, Zeros, and Time Responses 76
4.9 Frequency Response 85
4.10 Fourier Transform 92
4.11 Models Frequently Encountered 97
4.12 Modeling Errors for Linear Systems 99
4.13 Bounds for Modeling Errors 103
4.14 Summary 104
4.15 Further Reading 108
4.16 Problems for the Reader 110

II SISO CONTROL ESSENTIALS 117

PREVIEW 119

5 ANALYSIS OF SISO CONTROL LOOPS 121
5.1 Preview 121
5.2 Feedback Structures 121
5.3 Nominal Sensitivity Functions 125
5.4 Closed-Loop Stability Based on the Characteristic Polynomial 127
5.5 Stability and Polynomial Analysis 128
5.6 Root Locus (RL) 134
5.7 Nominal Stability using Frequency Response 138
5.8 Relative Stability: Stability Margins and Sensitivity Peaks 143
5.9 Robustness 145
5.10 Summary 150
5.11 Further Reading 152
5.12 Problems for the Reader 154

6 CLASSICAL PID CONTROL 159
6.1 Preview 159
6.2 PID Structure 159
6.3 Empirical Tuning 162
6.4 Ziegler-Nichols (Z-N) Oscillation Method 162
6.5 Reaction Curve Based Methods 166
6.6 Lead-Lag Compensators 170
6.7 Distillation Column 171
6.8 Summary 174
6.9 Further Reading 175
6.10 Problems for the Reader 176

7 SYNTHESIS OF SISO CONTROLLERS 179
7.1 Preview 179
7.2 Polynomial Approach 179
7.3 PI and PID Synthesis Revisited by using Pole Assignment 187
7.4 Smith Predictor 189
7.5 Summary 191
7.6 Further Reading 192
7.7 Problems for the Reader 193

III SISO CONTROL DESIGN 197

PREVIEW 199

8 FUNDAMENTAL LIMITATIONS IN SISO CONTROL 201
8.1 Preview 201
8.2 Sensors 202
8.3 Actuators 203
8.4 Disturbances 206
8.5 Model-Error Limitations 206
8.6 Structural Limitations 207
8.7 An Industrial Application (Hold-Up Effect in Reversing Mill) 222
8.8 Remedies 225
8.9 Design Homogeneity, Revisited 232
8.10 Summary 232
8.11 Further Reading 235
8.12 Problems for the Reader 237

9 FREQUENCY-DOMAIN DESIGN LIMITATIONS 241
9.1 Preview 241
9.2 Bode's Integral Constraints on Sensitivity 242
9.3 Integral Constraints on Complementary Sensitivity 246
9.4 Poisson Integral Constraint on Sensitivity 249
9.5 Poisson Integral Constraint on Complementary Sensitivity 254
9.6 Example of Design Trade-offs 256
9.7 Summary 259
9.8 Further Reading 260
9.9 Problems for the Reader 263

10 ARCHITECTURAL ISSUES IN SISO CONTROL 265
10.1 Preview 265
10.2 Models for Deterministic Disturbances and References 265
10.3 Internal Model Principle for Disturbances 267
10.4 Internal Model Principle for Reference Tracking 271
10.5 Feedforward 271
10.6 Industrial Applications of Feedforward Control 279
10.7 Cascade Control 281
10.8 Summary 285

10.9 Further Reading 288
10.10 Problems for the Reader 289

11 DEALING WITH CONSTRAINTS 293
11.1 Preview 293
11.2 Wind-Up 294
11.3 Anti-Wind-up Scheme 295
11.4 State Saturation 301
11.5 Introduction to Model Predictive Control 306
11.6 Summary 306
11.7 Further Reading 307
11.8 Problems for the Reader 309

IV DIGITAL COMPUTER CONTROL 315

PREVIEW 317

12 MODELS FOR SAMPLED-DATA SYSTEMS 319
12.1 Preview 319
12.2 Sampling 319
12.3 Signal Reconstruction 321
12.4 Linear Discrete-Time Models 322
12.5 The Shift Operator 322
12.6 Z-Transform 323
12.7 Discrete Transfer Functions 324
12.8 Discrete Delta-Domain Models 328
12.9 Discrete Delta-Transform 331
12.10 Discrete Transfer Functions (Delta Form) 335
12.11 Transfer Functions and Impulse Responses 336
12.12 Discrete System Stability 336
12.13 Discrete Models for Sampled Continuous Systems 337
12.14 Using Continuous State Space Models 340
12.15 Frequency Response of Sampled-Data Systems 342
12.16 Summary 345
12.17 Further Reading 348
12.18 Problems for the Reader 349

13 DIGITAL CONTROL 353

13.1 Preview 353
13.2 Discrete-Time Sensitivity Functions 353
13.3 Zeros of Sampled-Data Systems 355
13.4 Is a Dedicated Digital Theory Really Necessary? 357
13.5 Approximate Continuous Designs 358
13.6 At-Sample Digital Design 362
13.7 Internal Model Principle for Digital Control 372
13.8 Fundamental Performance Limitations 376
13.9 Summary 380
13.10 Further Reading 381
13.11 Problems for the Reader 383

14 HYBRID CONTROL 387
14.1 Preview 387
14.2 Hybrid Analysis 387
14.3 Models for Hybrid Control Systems 387
14.4 Analysis of Intersample Behavior 391
14.5 Repetitive Control Revisited 393
14.6 Poisson Summation Formula 394
14.7 Summary 396
14.8 Further Reading 397
14.9 Problems for the Reader 398

V ADVANCED SISO CONTROL 403

PREVIEW 405

15 SISO CONTROLLER PARAMETERIZATIONS 407
15.1 Preview 407
15.2 Open-Loop Inversion Revisited 407
15.3 Affine Parameterization: The Stable Case 408
15.4 PID Synthesis by using the Affine Parameterization 418
15.5 Affine Parameterization for Systems Having Time Delays 427
15.6 Undesirable Closed-Loop Poles 430
15.7 Affine Parameterization: The Unstable Open-Loop Case 438
15.8 Discrete-Time Systems 446
15.9 Summary 447

15.10 Further reading 451
15.11 Problems for the Reader 453

16 CONTROL DESIGN BASED ON OPTIMIZATION 457
16.1 Preview 457
16.2 Optimal Q (Affine) Synthesis 458
16.3 Robust Control Design with Confidence Bounds 464
16.4 Cheap Control Fundamental Limitations 478
16.5 Frequency-Domain Limitations Revisited 480
16.6 Summary 482
16.7 Further Reading 483
16.8 Problems for the Reader 486

17 LINEAR STATE SPACE MODELS 491
17.1 Preview 491
17.2 Linear Continuous-Time State Space Models 491
17.3 Similarity Transformations 492
17.4 Transfer Functions Revisited 494
17.5 From Transfer Function to State Space Representation 496
17.6 Controllability and Stabilizability 498
17.7 Observability and Detectability 508
17.8 Canonical Decomposition 513
17.9 Pole-Zero Cancellation and System Properties 516
17.10 Summary 519
17.11 Further Reading 521
17.12 Problems for the Reader 523

18 SYNTHESIS VIA STATE SPACE METHODS 527
18.1 Preview 527
18.2 Pole Assignment by State Feedback 527
18.3 Observers 531
18.4 Combining State Feedback with an Observer 537
18.5 Transfer-Function Interpretations 539
18.6 Reinterpretation of the Affine Parameterization of all Stabilizing Controllers 545
18.7 State Space Interpretation of Internal Model Principle 546
18.8 Trade-Offs in State Feedback and Observers 551

18.9 Dealing with Input Constraints in the Context of State-Estimate Feedback 552
18.10 Summary 553
18.11 Further Reading 555
18.12 Problems for the Reader 556

19 INTRODUCTION TO NONLINEAR CONTROL 559
19.1 Preview 559
19.2 Linear Control of a Nonlinear Plant 559
19.3 Switched Linear Controllers 564
19.4 Control of Systems with Smooth Nonlinearities 567
19.5 Static Input Nonlinearities 567
19.6 Smooth Dynamic Nonlinearities for Stable and Stably Invertible Models 568
19.7 Disturbance Issues in Nonlinear Control 575
19.8 More General Plants with Smooth Nonlinearities 580
19.9 Nonsmooth Nonlinearities 583
19.10 Stability of Nonlinear Systems 585
19.11 Generalized Feedback Linearization for nonstability-Invertible Plants 595
19.12 Summary 603
19.13 Further Reading 604
19.14 Problems for the Reader 607

VI MIMO CONTROL ESSENTIALS 609

PREVIEW 611

20 ANALYSIS OF MIMO CONTROL LOOPS 613
20.1 Preview 613
20.2 Motivational Examples 613
20.3 Models for Multivariable Systems 615
20.4 The Basic MIMO Control Loop 624
20.5 Closed-Loop Stability 626
20.6 Steady-State Response for Step Inputs 630
20.7 Frequency-Domain Analysis 631
20.8 Robustness Issues 641
20.9 Summary 644
20.10 Further Reading 646

20.11 Problems for the Reader 648

21 EXPLOITING SISO TECHNIQUES IN MIMO CONTROL 653

21.1 Preview 653
21.2 Completely Decentralized Control 653
21.3 Pairing of Inputs and Outputs 657
21.4 Robustness Issues in Decentralized Control 660
21.5 Feedforward Action in Decentralized Control 662
21.6 Converting MIMO Problems to SISO Problems 664
21.7 Industrial Case Study (Strip Flatness Control) 666
21.8 Summary 670
21.9 Further Reading 671
21.10 Problems for the Reader 672

VII MIMO CONTROL DESIGN 675

PREVIEW 677

22 DESIGN VIA OPTIMAL CONTROL TECHNIQUES 679

22.1 Preview 679
22.2 State-Estimate Feedback 679
22.3 Dynamic Programming and Optimal Control 682
22.4 The Linear Quadratic Regulator (LQR) 685
22.5 Properties of the Linear Quadratic Optimal Regulator 687
22.6 Model Matching Based on Linear Quadratic Optimal Regulators 692
22.7 Discrete-Time Optimal Regulators 695
22.8 Connections to Pole Assignment 696
22.9 Observer Design 698
22.10 Linear Optimal Filters 699
22.11 State-Estimate Feedback 713
22.12 Transfer-Function Interpretation 713
22.13 Achieving Integral Action in LQR Synthesis 716
22.14 Industrial Applications 718
22.15 Summary 730
22.16 Further Reading 733
22.17 Problems for the Reader 736

23 MODEL PREDICTIVE CONTROL 739

23.1 Preview 739
23.2 Anti-Wind-Up Revisited 740
23.3 What is Model Predictive Control? 744
23.4 Stability 748
23.5 Linear Models with Quadratic Cost Function 751
23.6 State Estimation and Disturbance Prediction 756
23.7 Rudder Roll Stabilization of Ships 758
23.8 Summary 762
23.9 Further Reading 763
23.10 Problems for the Reader 766

24 FUNDAMENTAL LIMITATIONS IN MIMO CONTROL 771
24.1 Preview 771
24.2 Closed-Loop Transfer Function 772
24.3 MIMO Internal Model Principle 773
24.4 The Cost of the Internal Model Principle 773
24.5 RHP Poles and Zeros 774
24.6 Time-Domain Constraints 775
24.7 Poisson Integral Constraints on MIMO Complementary Sensitivity 780
24.8 Poisson Integral Constraints on MIMO Sensitivity 782
24.9 Interpretation 783
24.10 An Industrial Application: Sugar Mill 785
24.11 Nonsquare Systems 796
24.12 Discrete-Time Systems 800
24.13 Summary 800
24.14 Further Reading 802
24.15 Problems for the Reader 804

VIII ADVANCED MIMO CONTROL 807

PREVIEW 809

25 MIMO CONTROLLER PARAMETERIZATIONS 811
25.1 Preview 811
25.2 Affine Parameterization: Stable MIMO Plants 811
25.3 Achieved Sensitivities 813
25.4 Dealing with Model Relative Degree 813

25.5 Dealing with NMP Zeros 824
25.6 Affine Parameterization: Unstable MIMO Plants 841
25.7 State Space Implementation 844
25.8 Summary 847
25.9 Further Reading 848
25.10 Problems for the Reader 850

26 DECOUPLING 853
26.1 Preview 853
26.2 Stable Systems 854
26.3 Pre- and PostDiagonalization 861
26.4 Unstable Systems 863
26.5 Zeros of Decoupled and Partially Decoupled Systems 873
26.6 Frequency-Domain Constraints for Dynamically Decoupled Systems 876
26.7 The Cost of Decoupling 878
26.8 Input Saturation 882
26.9 MIMO Anti-Wind-Up Mechanism 883
26.10 Summary 891
26.11 Further Reading 893
26.12 Problems for the Reader 895

APPENDICES (*These can be viewed on the accompanying CD-ROM or at: http://www.prenhall.com/goodwin.*)

A NOTATION, SYMBOLS, AND ACRONYMS

B SMITH–MCMILLAN FORMS
B.1 Introduction
B.2 Polynomial Matrices
B.3 Smith Form for Polynomial Matrices
B.4 Smith–McMillan Form for Rational Matrices
B.5 Poles and Zeros
B.6 Matrix Fraction Descriptions (MFD)

C RESULTS FROM ANALYTIC FUNCTION THEORY
C.1 Introduction
C.2 Independence of Path
C.3 Simply Connected Domains

C.4 Functions of a Complex Variable
C.5 Derivatives and Differentials
C.6 Analytic Functions
C.7 Integrals Revisited
C.8 Poisson and Jensen Integral Formulas
C.9 Application of the Poisson–Jensen Formula to Certain Rational Functions
C.10 Bode's Theorems

D PROPERTIES OF CONTINUOUS-TIME RICCATI EQUATIONS

D.1 Solutions of the CTDRE
D.2 Solutions of the CTARE
D.3 The stabilizing solution of the CTARE
D.4 Convergence of Solutions of the CTARE to the Stabilizing Solution of the CTARE
D.5 Duality between Linear Quadratic Regulator and Optimal Linear Filter

E MATLAB SUPPORT