

Contents

Preface vii

1. **Computer Control 1**
 - 1.1 Introduction 1
 - 1.2 Computer Technology 2
 - 1.3 Computer-Control Theory 11
 - 1.4 Inherently Sampled Systems 22
 - 1.5 How Theory Developed 25
 - 1.6 Notes and References 28
2. **Discrete-Time Systems 30**
 - 2.1 Introduction 30
 - 2.2 Sampling Continuous-Time Signals 31
 - 2.3 Sampling a Continuous-Time State-Space System 32
 - 2.4 Discrete-Time Systems 42
 - 2.5 Changing Coordinates in State-Space Models 44
 - 2.6 Input-Output Models 46
 - 2.7 The z-Transform 53
 - 2.8 Poles and Zeros 61
 - 2.9 Selection of Sampling Rate 66
 - 2.10 Problems 68
 - 2.11 Notes and References 75
3. **Analysis of Discrete-Time Systems 77**
 - 3.1 Introduction 77
 - 3.2 Stability 77
 - 3.3 Sensitivity and Robustness 89
 - 3.4 Controllability, Reachability, Observability, and Detectability 93
 - 3.5 Analysis of Simple Feedback Loops 103
 - 3.6 Problems 114
 - 3.7 Notes and References 118
4. **Pole-Placement Design: A State-Space Approach 120**
 - 4.1 Introduction 120
 - 4.2 Control-System Design 121

- 4.3 Regulation by State Feedback 124
- 4.4 Observers 135
- 4.5 Output Feedback 141
- 4.6. The Servo Problem 147
- 4.7 A Design Example 156
- 4.8 Conclusions 160
- 4.9 Problems 161
- 4.10 Notes and References 164
- 5. Pole-Placement Design: A Polynomial Approach 165**
 - 5.1 Introduction 165
 - 5.2 A Simple Design Problem 166
 - 5.3 The Diophantine Equation 170
 - 5.4 More Realistic Assumptions 175
 - 5.5 Sensitivity to Modeling Errors 183
 - 5.6 A Design Procedure 186
 - 5.7 Design of a Controller for the Double Integrator 195
 - 5.8 Design of a Controller for the Harmonic Oscillator 203
 - 5.9 Design of a Controller for a Flexible Robot Arm 208
 - 5.10 Relations to Other Design Methods 213
 - 5.11 Conclusions 220
 - 5.12 Problems 220
 - 5.13 Notes and References 223
- 6. Design: An Overview 224**
 - 6.1 Introduction 224
 - 6.2 Operational Aspects 225
 - 6.3 Principles of Structuring 229
 - 6.4 A Top-Down Approach 230
 - 6.5 A Bottom-Up Approach 233
 - 6.6 Design of Simple Loops 237
 - 6.7 Conclusions 240
 - 6.8 Problems 241
 - 6.9 Notes and References 241
- 7. Process-Oriented Models 242**
 - 7.1 Introduction 242
 - 7.2 A Computer-Controlled System 243
 - 7.3 Sampling and Reconstruction 244
 - 7.4 Aliasing or Frequency Folding 249
 - 7.5 Designing Controllers with Predictive First-Order Hold 256
 - 7.6 The Modulation Model 262
 - 7.7 Frequency Response 268
 - 7.8 Pulse-Transfer-Function Formalism 278
 - 7.9 Multirate Sampling 286
 - 7.10 Problems 289
 - 7.11 Notes and References 291

- 8. Approximating Continuous- Time Controllers 293**
 - 8.1 Introduction 293
 - 8.2 Approximations Based on Transfer Functions 293
 - 8.3 Approximations Based on State Models 301
 - 8.4 Frequency-Response Design Methods 305
 - 8.5 Digital PID-Controllers 306
 - 8.6 Conclusions 320
 - 8.7 Problems 320
 - 8.8 Notes and References 323
- 9. Implementation of Digital Controllers 324**
 - 9.1 Introduction 324
 - 9.2 An Overview 325
 - 9.3 Prefiltering and Computational Delay 328
 - 9.4 Nonlinear Actuators 331
 - 9.5 Operational Aspects 336
 - 9.6 Numerics 340
 - 9.7 Realization of Digital Controllers 349
 - 9.8 Programming 360
 - 9.9 Conclusions 363
 - 9.10 Problems 364
 - 9.11 Notes and References 368
- 10. Disturbance Models 370**
 - 10.1 Introduction 370
 - 10.2 Reduction of Effects of Disturbances 371
 - 10.3 Piecewise Deterministic Disturbances 373
 - 10.4 Stochastic Models of Disturbances 376
 - 10.5 Continuous-Time Stochastic Processes 397
 - 10.6 Sampling a Stochastic Differential Equation 402
 - 10.7 Conclusions 403
 - 10.8 Problems 404
 - 10.9 Notes and References 407
- 11. Optimal Design Methods: A State-Space Approach 408**
 - 11.1 Introduction 408
 - 11.2 Linear Quadratic Control 413
 - 11.3 Prediction and Filtering Theory 429
 - 11.4 Linear Quadratic Gaussian Control 436
 - 11.5 Practical Aspects 440
 - 11.6 Conclusions 441
 - 11.7 Problems 441
 - 11.8 Notes and References 446
- 12. Optimal Design Methods: A Polynomial Approach 447**
 - 12.1 Introduction 447
 - 12.2 Problem Formulation 448
 - 12.3 Optimal Prediction 453
 - 12.4 Minimum-Variance Control 460

| | | |
|------------|---|------------|
| 12.5 | Linear Quadratic Gaussian (LQG) Control | 470 |
| 12.6 | Practical Aspects | 487 |
| 12.7 | Conclusions | 495 |
| 12.8 | Problems | 496 |
| 12.9 | Notes and References | 504 |
| 13. | Identification | 505 |
| 13.1 | Introduction | 505 |
| 13.2 | Mathematical Model Building | 506 |
| 13.3 | System Identification | 506 |
| 13.4 | The Principle of Least Squares | 509 |
| 13.5 | Recursive Computations | 514 |
| 13.6 | Examples | 521 |
| 13.7 | Summary | 526 |
| 13.8 | Problems | 526 |
| 13.9 | Notes and References | 527 |
| A. | Examples | 528 |
| B. | Matrices | 533 |
| B.1 | Matrix Functions | 533 |
| B.2 | Matrix-Inversion Lemma | 536 |
| B.3 | Notes and References | 536 |
| | Bibliography | 537 |
| | Index | 549 |