Contents

Preface 15
About the Authors 27

CHAPTER 1 *Introduction to Control Systems 29*

1.1 Introduction 30
1.2 Brief History of Automatic Control 33
1.3 Examples of Control Systems 39
1.4 Engineering Design 46
1.5 Control System Design 47
1.6 Mechatronic Systems 50
1.7 Green Engineering 54
1.8 The Future Evolution of Control Systems 55
1.9 Design Examples 57
1.10 Sequential Design Example: Disk Drive Read System 62
1.11 Summary 63
Skills Check 63 • Exercises 66 • Problems 68 • Advanced Problems 73 • Design Problems 75 • Terms and Concepts 78

CHAPTER 2 *Mathematical Models of Systems 79*

2.1 Introduction 80
2.2 Differential Equations of Physical Systems 80
2.3 Linear Approximations of Physical Systems 85
2.4 The Laplace Transform 88
2.5 The Transfer Function of Linear Systems 95
2.6 Block Diagram Models 107
2.7 Signal-Flow Graph Models 112
2.8 Design Examples 119
2.9 The Simulation of Systems Using Control Design Software 136
2.10 Sequential Design Example: Disk Drive Read System 150
2.11 Summary 153
Skills Check 154 • Exercises 158 • Problems 164 • Advanced Problems 176 • Design Problems 178 • Computer Problems 180 • Terms and Concepts 182

CHAPTER 3 *State Variable Models 184*

3.1 Introduction 185
3.2 The State Variables of a Dynamic System 185
3.3 The State Differential Equation 188

3.4 Signal-Flow Graph and Block Diagram Models 194
3.5 Alternative Signal-Flow Graph and Block Diagram Models 205
3.6 The Transfer Function from the State Equation 209
3.7 The Time Response and the State Transition Matrix 210
3.8 Design Examples 214
3.9 Analysis of State Variable Models Using Control Design Software 228
3.10 Sequential Design Example: Disk Drive Read System 232
3.11 Summary 235
Skills Check 236 • Exercises 239 • Problems 242 • Advanced Problems 250 • Design Problems 252 • Computer Problems 253 • Terms and Concepts 254

CHAPTER 4 ***Feedback Control System Characteristics 256***

4.1 Introduction 257
4.2 Error Signal Analysis 259
4.3 Sensitivity of Control Systems to Parameter Variations 261
4.4 Disturbance Signals in a Feedback Control System 264
4.5 Control of the Transient Response 269
4.6 Steady-State Error 272
4.7 The Cost of Feedback 274
4.8 Design Examples 275
4.9 Control System Characteristics Using Control Design Software 285
4.10 Sequential Design Example: Disk Drive Read System 291
4.11 Summary 295
Skills Check 296 • Exercises 300 • Problems 304 • Advanced Problems 310 • Design Problems 313 • Computer Problems 317 • Terms and Concepts 320

CHAPTER 5 ***The Performance of Feedback Control Systems 321***

5.1 Introduction 322
5.2 Test Input Signals 322
5.3 Performance of Second-Order Systems 325
5.4 Effects of a Third Pole and a Zero on the Second-Order System Response 330
5.5 The s-Plane Root Location and the Transient Response 335
5.6 The Steady-State Error of Feedback Control Systems 337
5.7 Performance Indices 344
5.8 The Simplification of Linear Systems 349
5.9 Design Examples 352
5.10 System Performance Using Control Design Software 364
5.11 Sequential Design Example: Disk Drive Read System 370

5.12 Summary 372
Skills Check 373 • Exercises 376 • Problems 379 • Advanced Problems 385 • Design Problems 387 • Computer Problems 390 • Terms and Concepts 393

CHAPTER 6 *The Stability of Linear Feedback Systems 394*

6.1 The Concept of Stability 395
6.2 The Routh–Hurwitz Stability Criterion 399
6.3 The Relative Stability of Feedback Control Systems 407
6.4 The Stability of State Variable Systems 408
6.5 Design Examples 411
6.6 System Stability Using Control Design Software 419
6.7 Sequential Design Example: Disk Drive Read System 425
6.8 Summary 427
Skills Check 428 • Exercises 431 • Problems 433 • Advanced Problems 438 • Design Problems 441 • Computer Problems 443 • Terms and Concepts 445

CHAPTER 7 *The Root Locus Method 446*

7.1 Introduction 447
7.2 The Root Locus Concept 447
7.3 The Root Locus Procedure 452
7.4 Parameter Design by the Root Locus Method 466
7.5 Sensitivity and the Root Locus 472
7.6 PID Controllers 477
7.7 Negative Gain Root Locus 488
7.8 Design Examples 493
7.9 The Root Locus Using Control Design Software 502
7.10 Sequential Design Example: Disk Drive Read System 508
7.11 Summary 510
Skills Check 514 • Exercises 518 • Problems 522 • Advanced Problems 531 • Design Problems 535 • Computer Problems 541 • Terms and Concepts 543

CHAPTER 8 *Frequency Response Methods 545*

8.1 Introduction 546
8.2 Frequency Response Plots 548
8.3 Frequency Response Measurements 569
8.4 Performance Specifications in the Frequency Domain 571
8.5 Log-Magnitude and Phase Diagrams 574
8.6 Design Examples 575
8.7 Frequency Response Methods Using Control Design Software 584

8.8 Sequential Design Example: Disk Drive Read System 589
8.9 Summary 591
Skills Check 596 • Exercises 601 • Problems 604 • Advanced Problems 613 • Design Problems 615 • Computer Problems 618 • Terms and Concepts 620

CHAPTER 9 *Stability in the Frequency Domain 622*

9.1 Introduction 623
9.2 Mapping Contours in the *s*-Plane 624
9.3 The Nyquist Criterion 630
9.4 Relative Stability and the Nyquist Criterion 641
9.5 Time-Domain Performance Criteria in the Frequency Domain 648
9.6 System Bandwidth 655
9.7 The Stability of Control Systems with Time Delays 655
9.8 Design Examples 659
9.9 PID Controllers in the Frequency Domain 677
9.10 Stability in the Frequency Domain Using Control Design Software 678
9.11 Sequential Design Example: Disk Drive Read System 686
9.12 Summary 689
Skills Check 698 • Exercises 701 • Problems 707 • Advanced Problems 717 • Design Problems 720 • Computer Problems 725 • Terms and Concepts 727

CHAPTER 10 *The Design of Feedback Control Systems 728*

10.1 Introduction 729
10.2 Approaches to System Design 730
10.3 Cascade Compensators 731
10.4 Phase-Lead Design Using the Bode Plot 735
10.5 Phase-Lead Design Using the Root Locus 741
10.6 System Design Using Integration Compensators 747
10.7 Phase-Lag Design Using the Root Locus 750
10.8 Phase-Lag Design Using the Bode Plot 753
10.9 Design on the Bode Plot Using Analytical Methods 758
10.10 Systems with a Prefilter 759
10.11 Design for Deadbeat Response 762
10.12 Design Examples 764
10.13 System Design Using Control Design Software 774
10.14 Sequential Design Example: Disk Drive Read System 781
10.15 Summary 783
Skills Check 784 • Exercises 788 • Problems 792 • Advanced Problems 801 • Design Problems 804 • Computer Problems 808 • Terms and Concepts 811

CHAPTER 11 *The Design of State Variable Feedback Systems* 812

11.1 Introduction 813
11.2 Controllability and Observability 813
11.3 Full-State Feedback Control Design 819
11.4 Observer Design 825
11.5 Integrated Full-State Feedback and Observer 829
11.6 Reference Inputs 835
11.7 Optimal Control Systems 837
11.8 Internal Model Design 845
11.9 Design Examples 848
11.10 State Variable Design Using Control Design Software 855
11.11 Sequential Design Example: Disk Drive Read System 860
11.12 Summary 862
Skills Check 862 • Exercises 866 • Problems 868 • Advanced Problems 872 • Design Problems 875 • Computer Problems 878 • Terms and Concepts 881

CHAPTER 12 *Robust Control Systems* 882

12.1 Introduction 883
12.2 Robust Control Systems and System Sensitivity 884
12.3 Analysis of Robustness 888
12.4 Systems with Uncertain Parameters 890
12.5 The Design of Robust Control Systems 892
12.6 The Design of Robust PID-Controlled Systems 896
12.7 The Robust Internal Model Control System 900
12.8 Design Examples 903
12.9 The Pseudo-Quantitative Feedback System 914
12.10 Robust Control Systems Using Control Design Software 916
12.11 Sequential Design Example: Disk Drive Read System 919
12.12 Summary 921
Skills Check 923 • Exercises 927 • Problems 929 • Advanced Problems 933 • Design Problems 936 • Computer Problems 941 • Terms and Concepts 944

CHAPTER 13 *Digital Control Systems* 945

13.1 Introduction 946
13.2 Digital Computer Control System Applications 946
13.3 Sampled-Data Systems 948
13.4 The z-Transform 951
13.5 Closed-Loop Feedback Sampled-Data Systems 955
13.6 Performance of a Sampled-Data, Second-Order System 959

13.7 Closed-Loop Systems with Digital Computer Compensation 961
13.8 The Root Locus of Digital Control Systems 964
13.9 Implementation of Digital Controllers 968
13.10 Design Examples 968
13.11 Digital Control Systems Using Control Design Software 977
13.12 Sequential Design Example: Disk Drive Read System 982
13.13 Summary 984
Skills Check 984 • Exercises 988 • Problems 990 • Advanced Problems 992 • Design Problems 993 • Computer Problems 995 • Terms and Concepts 996

References 997

Index 1014

WEB RESOURCES

APPENDIX A *MATLAB Basics*
APPENDIX B *MathScript RT Module Basics*
APPENDIX C *Symbols, Units, and Conversion Factors*
APPENDIX D *Laplace Transform Pairs*
APPENDIX E *An Introduction to Matrix Algebra*
APPENDIX F *Decibel Conversion*
APPENDIX G *Complex Numbers*
APPENDIX H *z-Transform Pairs*
APPENDIX I *Discrete-Time Evaluation of the Time Response*
APPENDIX J *Design Aids*