

Contents



Preface

xiii

Part I Introduction to MATLAB

1

1 Review of Classical Control

1

1.1	Introduction	1
1.2	Transfer Functions	2
1.2.1	<i>Frequency Response</i>	3
1.3	Convolution and the Impulse Response	5
1.4	Stability	7
1.4.1	<i>Stability of the Zero-Input Response: Asymptotic Stability</i>	7
1.4.2	<i>Stability of the Zero-State Response: BIBO Stability</i>	8
1.5	First and Second Order System	10
1.5.1	<i>First Order Systems</i>	10
1.5.2	<i>Second Order Systems</i>	11
1.5.3	<i>Effects of Adding Poles and Zeros</i>	16
1.6	Feedback Control	19
1.6.1	<i>Feedback Properties</i>	19
1.6.2	<i>Closed Loop Stability</i>	24
1.6.3	<i>Steady State Error</i>	24
1.7	Root Locus	27
1.7.1	<i>Zero Degree Root Locus</i>	30
1.8	Frequency Response Analysis	30
1.8.1	<i>Bode Plot</i>	31
1.8.2	<i>Nyquist Plot and Stability Criterion</i>	31
1.8.3	<i>Gain and Phase Margins</i>	32
1.8.4	<i>Relationship between Open and Closed Loop Behavior</i>	35

1.9 Computer-aided Control System Design	37
1.10 Problems	38

2 *Introduction to MATLAB* 44

2.1 On-screen Help	44
2.2 File Management	47
2.3 Data Structures: Vectors and Matrices	49
2.3.1 <i>Matrix Addressing and Subscripting</i>	52
2.3.2 <i>Special Matrices</i>	53
2.3.3 <i>Strings</i>	55
2.4 Mathematical Operations and Functions	55
2.4.1 <i>Elementary Operations</i>	55
2.4.2 <i>Elementary Mathematical Functions</i>	57
2.4.3 <i>Data Analysis: Column Oriented Functions</i>	57
2.5 Polynomials	58
2.6 Plotting and Graphics	61
2.6.1 <i>Multiple Curves</i>	61
2.7 Examples	62
2.8 Problems	72

3 *Programming in MATLAB* 77

3.1 Relational and Logical Operators	77
3.2 Loops and Conditional Structures	77
3.3 M-files: Scripts and Function Files	80
3.3.1 <i>Scripts</i>	84
3.3.2 <i>Functions</i>	85
3.3.3 <i>Creating M-files</i>	86
3.4 Text Strings as Macros	86
3.5 Programming Utilities	87
3.6 Program Examples	88
3.7 Problems	91

4 *Classical Control Commands* 94

4.1 Time Domain	94
4.2 Frequency Domain	95
4.2.1 <i>Stability Margins</i>	96
4.3 Root Locus	97
4.4 Transfer Function Utilities	98

4.5 Examples	100
4.6 Problems	109

5 *Introduction to State Space Analysis*

117

5.1 Introduction	117
5.2 State Space Realizations	118
5.3 Asymptotic Stability	122
5.4 State Space Analysis Using MATLAB	122
5.5 System Interconnections	128
5.5.1 Series (Cascade) Connection	128
5.5.2 Parallel Connection	131
5.5.3 Feedback Connection	132
5.5.4 Append, Blkbuild, and Connect	134
5.6 Feedback and Sensitivity Measures	139
5.7 Problems	140

6 *Introduction to SIMULINK*

143

6.1 Basic Steps in Model Building	144
6.2 SIMULINK Commands	148
6.2.1 Simulation From the Command Line	148
6.2.2 Choice of Integration Algorithms	150
6.2.3 Linearization	150
6.2.4 Data Interpolation	153
6.3 Examples	153
6.4 Advanced Features	164
6.5 Problems	164

Part II *Control Systems Design*

167

7 *Classical Design*

7.1 Introduction	167
7.1.1 Root Locus	167
7.1.2 Bode Plots	169
7.2 Compensation	170
7.3 Proportional-integral-derivative Control	171
7.3.1 Ziegler-Nichols Method	171
7.3.2 Analytical Method	173
7.3.3 PD Control	175

7.4 Lead Compensation	177
7.4.1 Root Locus Design	180
7.4.2 Root Locus—Geometric Method	181
7.4.3 Root Locus—Analytical Method	183
7.4.4 Lead compensation—Bode Design	185
7.4.5 Bode Design—Analytical Method	189
7.4.6 Comparison of PD Controller and Lead Compensator	192
7.5 Lag Compensation	194
7.5.1 Root Locus Design	194
7.5.2 Root Locus—Analytical Method	196
7.5.3 Lag Compensation—Bode Design	197
7.5.4 Bode Design—Analytical Method	202
7.5.5 Comparison of Lag Compressor and PI Controller	205
7.6 General Compensation	205
7.7 Stability Margins of Nonminimum Phase Systems	210
7.8 Appendix: Design Programs	214
7.9 Problems	216
8 State Space Design of Regulator Systems	220
8.1 Introduction	220
8.2 Pole Placement (State Feedback)	221
8.2.1 Transfer Function Analysis	224
8.2.2 MATLAB Commands	225
8.3 Observer Design	230
8.3.1 Transfer Function Analysis	232
8.4 Reduced Order Observer Design	238
8.4.1 Transfer Function Analysis	240
8.5 Comments Regarding State Space Design	247
8.6 Appendix: Design Programs	248
8.7 Problems	250
9 Digital Control	253
9.1 Introduction	253
9.2 Difference Equations	254
9.3 Spectrum of Sampled Signal	256
9.3.1 Sampling Theorem	258
9.3.2 Aliasing	258
9.4 The z-Transform	260
9.5 Discrete State Space Model	262
9.6 Mapping the s-Plane to the z-Plane	262
9.7 System Type and Steady State Error	265

9.8	Simulation of Digital Control Systems	267
9.8.1	<i>Impulse Invariant Transformation</i>	267
9.8.2	<i>Zero Order Hold Equivalence</i>	268
9.8.3	<i>Numerical Integration Methods</i>	270
9.9	MATLAB Discrete Commands	273
9.10	The Warping Problem	278
9.10.1	<i>Prewarping</i>	279
9.10.2	<i>Critical Frequency Prewarping</i>	281
9.11	Digital Compensators	283
9.11.1	<i>Proportional-Integral-Derivative Control</i>	284
9.11.2	<i>PID—Analytical Technique</i>	287
9.11.3	<i>Lead-Lag Compensation</i>	290
9.11.4	<i>The w-Transform</i>	292
9.11.5	<i>Compensator Delay</i>	298
9.12	Discrete State Space Design	298
9.13	Appendix	298
9.13.1	<i>Programs</i>	298
9.13.2	<i>Tables of z-Transform and ZOH Equivalents</i>	300
9.14	Problems	301

10 Algebraic Design 308

10.1	Introduction	308
10.2	Design Constraints	310
10.3	Implementable Transfer Functions	312
10.4	Selection of Desired Closed Loop Transfer Function	312
10.5	Optimal Transfer Functions: ITAE and Symmetric Root Locus	314
10.6	Unity Feedback Configuration	316
10.6.1	<i>Solving the Design Equation</i>	317
10.7	Two-Parameter Configuration (RST Compensator)	324
10.7.1	<i>Realization of the RST Compensator</i>	325
10.8	Plant Input/Output Feedback Configuration	332
10.9	Appendix: Design Programs	335
10.10	Problems	339

11 Random Signals and Systems Analysis 343

11.1	Introduction	343
11.2	Stochastic (Random) Processes	343
11.3	Vector Processes	346
11.4	Response of Linear Systems to Random Inputs	347
11.5	MATLAB Signal Processing Commands	348
11.6	Appendix: Example Program	365

12 Linear Quadratic Control

366

12.1	The Linear Quadratic Regulator Problem	367
12.1.1	<i>LQR Solution Using the Minimum Principle</i>	367
12.1.2	<i>Generalizations of LQR</i>	369
12.1.3	<i>MATLAB Implementation</i>	370
12.1.4	<i>LQR Properties with Classical Interpretations</i>	371
12.2	Optimal Observer Design—Kalman-Bucy Filter	379
12.2.1	<i>Problem Formulation and Solution</i>	379
12.2.2	<i>MATLAB Implementation</i>	381
12.3	The Linear Quadratic Gaussian Problem	384
12.3.1	<i>LQG Problem Formulation and Solution</i>	384
12.4	Appendix: Design Programs	391
12.5	Problems	393

13 Robust/ H_∞ Control

395

13.1	Introduction	395
13.1.1	<i>Critique of LQG</i>	396
13.2	Performance Specifications and Robustness	396
13.2.1	<i>Nominal Performance of Feedback Systems</i>	397
13.2.2	<i>Nominal Performance: Multivariable Case</i>	400
13.2.3	<i>Novel Formulation of Classical Problems</i>	401
13.2.4	<i>Modeling Uncertainty</i>	403
13.2.5	<i>Robust Stability</i>	405
13.3	H_2 Optimization and Loop Transfer Recovery (LTR)	415
13.3.1	<i>H_2 Optimization</i>	415
13.3.2	<i>Loop Transfer Recovery (LTR) Method</i>	417
13.4	H_∞ Control	421
13.4.1	<i>A Brief History</i>	421
13.4.2	<i>Notation and Terminology</i>	422
13.4.3	<i>The Two-port Formulation of Control Problems</i>	425
13.5	H_∞ Control: Problem Formulation and Solution	428
13.5.1	<i>Problem Formulation and Assumptions</i>	428
13.5.2	<i>Problem Solution</i>	429
13.5.3	<i>Weights in H_∞ Control Problems</i>	431
13.6	Programs	438
13.7	Appendix	441
13.7.1	<i>Singular Value Decomposition (SVD)</i>	441
13.7.2	<i>Singular Values and Matrix Norms</i>	442
13.7.3	<i>The Supremum of Functions</i>	443
13.7.4	<i>Norms and Spaces</i>	444
13.8	Problems	448

Appendix Hardware Design Projects	455
A.1 Introduction	455
A.2 Magnetic Levitation	455
A.2.1 <i>System Models</i>	456
A.2.2 <i>Parameter Determination</i>	459
A.2.3 <i>Controller Design</i>	460
A.2.4 <i>Circuit Construction</i>	462
A.2.5 <i>Results</i>	464
A.3 Ball-on-Beam Balancer	465
A.3.1 <i>System Models</i>	465
A.3.2 <i>Parameter Determination</i>	469
A.3.3 <i>Controller Design</i>	470
A.3.4 <i>Construction</i>	470
A.3.5 <i>Results</i>	476
A.4 Inverted Pendulum on a Cart	476
A.4.1 <i>System Models</i>	476
A.4.2 <i>Parameter Determination</i>	478
A.4.3 <i>Controller Design</i>	480
A.4.4 <i>Construction</i>	484
A.4.5 <i>Results</i>	484
Bibliography	490
Index	493