

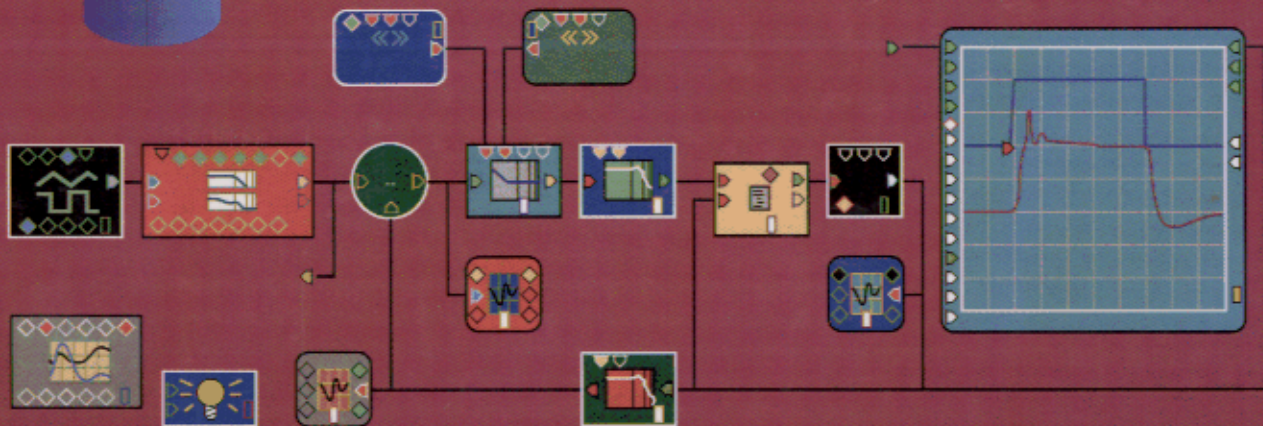
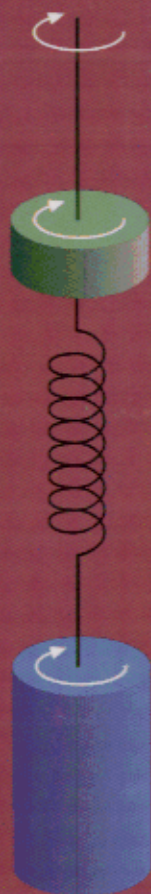


GEORGE ELLIS

CONTROL SYSTEM DESIGN GUIDE

USING YOUR COMPUTER TO UNDERSTAND
AND DIAGNOSE FEEDBACK CONTROLLERS

THIRD EDITION



Contents

Preface	xxi
Section I Applied Principles of Controls	1
Important Safety Guidelines for Readers	3
Chapter 1 Introduction to Controls	5
1.1 <i>Visual ModelQ</i> Simulation Environment	6
1.1.1 Installation of <i>Visual ModelQ</i>	6
1.1.2 Errata	6
1.2 The Control System	7
1.2.1 The Controller	7
1.2.2 The Machine	8
1.3 The Controls Engineer	8
Chapter 2 The Frequency Domain	11
2.1 The Laplace Transform	11
2.2 Transfer Functions	12
2.2.1 What Is s ?	12
2.2.1.1 DC Gain	13
2.2.2 Linearity, Time Invariance, and Transfer Functions	13
2.3 Examples of Transfer Functions	14
2.3.1 Transfer Functions of Controller Elements	15
2.3.1.1 Integration and Differentiation	15
2.3.1.2 Filters	15
2.3.1.3 Compensators	15
2.3.1.4 Delays	15

CONTENTS

2.3.2	Transfer Functions of Power Conversion	16
2.3.3	Transfer Functions of Physical Elements	16
2.3.4	Transfer Functions of Feedback	18
2.4	Block Diagrams	18
2.4.1	Combining Blocks	18
2.4.1.1	Simplifying a Feedback Loop	19
2.4.2	Mason's Signal Flow Graphs	20
2.4.2.1	Step-by-Step Procedure	20
2.5	Phase and Gain	22
2.5.1	Phase and Gain from Transfer Functions	23
2.5.2	Bode Plots: Phase and Gain versus Frequency	24
2.6	Measuring Performance	25
2.6.1	Command Response	25
2.6.2	Stability	27
2.6.3	Time Domain versus Frequency Domain	28
2.7	Questions	29
Chapter 3	Tuning a Control System	31
3.1	Closing Loops	31
3.1.1	The Source of Instability	32
3.2	A Detailed Review of the Model	34
3.2.1	Integrator	34
3.2.2	Power Converter	36
3.2.3	PI Control Law	37
3.2.4	Feedback Filter	38
3.3	The Open-Loop Method	39
3.4	Margins of Stability	40
3.4.1	Quantifying GM and PM	40
3.4.2	Experiment 3A: Understanding the Open-Loop Method	41
3.4.3	Open Loop, Closed Loop, and the Step Response	43
3.5	A Zone-Based Tuning Procedure	45
3.5.1	Zone One: Proportional	46
3.5.2	Zone Two: Integral	47
3.6	Variation in Plant Gain	48
3.6.1	Accommodating Changing Gain	50
3.7	Multiple (Cascaded) Loops	50
3.8	Saturation and Synchronization	51
3.8.1	Avoid Saturation When Tuning	54
3.9	Questions	54
Chapter 4	Delay in Digital Controllers	57
4.1	How Sampling Works	57

4.2	Sources of Delay in Digital Systems	58
4.2.1	Sample-and-Hold Delay	58
4.2.2	Calculation Delay	60
4.2.3	Velocity Estimation Delay	60
4.2.4	The Sum of the Delays	61
4.3	Experiment 4A: Understanding Delay in Digital Control	61
4.3.1	Tuning the Controller	62
4.4	Selecting the Sample Time	64
4.4.1	Aggressive Assumptions for General Systems	65
4.4.2	Aggressive Assumptions for Position-Based Motion Systems	65
4.4.3	Moderate and Conservative Assumptions	66
4.5	Questions	67
Chapter 5	The z-Domain	69
5.1	Introduction to the z -Domain	69
5.1.1	Definition of z	69
5.1.2	z -Domain Transfer Functions	70
5.1.3	Bilinear Transform	71
5.2	z Phasors	71
5.3	Aliasing	73
5.4	Experiment 5A: Aliasing	74
5.4.1	Bode Plots and Block Diagrams in z	76
5.4.2	DC Gain	76
5.5	From Transfer Function to Algorithm	76
5.6	Functions for Digital Systems	78
5.6.1	Digital Integrals and Derivatives	78
5.6.1.1	Simple Integration	78
5.6.1.2	Alternative Methods of Integration	80
5.6.2	Digital Derivatives	81
5.6.2.1	Inverse Trapezoidal Differentiation	82
5.6.2.2	Experiment 5B: Inverse Trapezoidal Differentiation	84
5.6.3	Sample-and-Hold	85
5.6.4	DAC/ADC: Converting to and from Analog	86
5.7	Reducing the Calculation Delay	87
5.8	Selecting a Processor	88
5.8.1	Fixed- and Floating-Point Math	88
5.8.2	Overrunning the Sample Time	89
5.8.3	Other Algorithms	90
5.8.4	Ease of Programming	90
5.8.5	The Processor's Future	90
5.8.6	Making the Selection	90

CONTENTS

5.9	Quantization	91
5.9.1	Limit Cycles and Dither	91
5.9.2	Offset and Limit Cycles	93
5.10	Questions	94
Chapter 6	Six Types of Controllers	97
6.1	Tuning in This Chapter	98
6.2	Using the Proportional Gain	98
6.2.1	P Control	99
6.2.1.1	How to Tune a Proportional Controller	100
6.3	Using the Integral Gain	102
6.3.1	PI Control	103
6.3.1.1	How to Tune a PI Controller	103
6.3.1.2	Analog PI Control	104
6.3.2	PI+ Control	107
6.3.2.1	Comparing PI+ and PDFF	108
6.3.2.2	How to Tune a PI+ Controller	108
6.4	Using the Differential Gain	111
6.4.1	PID Control	112
6.4.1.1	How to Tune a PID Controller	112
6.4.1.2	Noise and the Differential Gain	115
6.4.1.3	The Ziegler–Nichols Method	115
6.4.1.4	Popular Terminology for PID Control	117
6.4.1.5	Analog Alternative to PID: Lead-Lag	117
6.5	PID+ Control	118
6.5.1	How to Tune a PID+ Controller	119
6.6	PD Control	121
6.6.1	How to Tune a PD Controller	121
6.7	Choosing the Controller	124
6.8	Experiments 6A–6F	124
6.9	Questions	125
Chapter 7	Disturbance Response	127
7.1	Disturbances	128
7.1.1	Disturbance Response of a Power Supply	130
7.2	Disturbance Response of a Velocity Controller	134
7.2.1	Time Domain	136
7.2.1.1	Proportional Controller	137
7.2.2	Frequency Domain	137
7.3	Disturbance Decoupling	140
7.3.1	Applications for Disturbance Decoupling	141
7.3.1.1	Power Supplies	141
7.3.1.2	Multizone Temperature Controller	142

	7.3.1.3 Web Handling	143
	7.3.2 Experiment 7B: Disturbance Decoupling	145
	7.4 Questions	149
Chapter 8	Feed-Forward	151
	8.1 Plant-Based Feed-Forward	151
	8.1.1 Experiment 8A: Plant-Based Feed-Forward	152
	8.2 Feed-Forward and the Power Converter	154
	8.2.1 Experiment 8B: Power Converter Compensation	156
	8.2.2 Increasing the Bandwidth vs. Feed-Forward Compensation	159
	8.3 Delaying the Command Signal	160
	8.3.1 Experiment 8C: Command-Path Delay	161
	8.3.2 Experiment 8D: Power Converter Compensation and Command Path Delay	162
	8.3.3 Tuning and Clamping with Feed-Forward	164
	8.4 Variation in Plant and Power Converter Operation	165
	8.4.1 Variation of the Plant Gain	166
	8.4.2 Variation of the Power Converter Operation	167
	8.5 Feed-Forward for the Double-Integrating Plant	167
	8.6 Questions	168
Chapter 9	Filters in Control Systems	171
	9.1 Filters in Control Systems	171
	9.1.1 Filters in the Controller	172
	9.1.1.1 Using Low-Pass Filters to Reduce Noise and Resonance	172
	9.1.1.2 Using Low-Pass Filters to Reduce Aliasing	173
	9.1.1.3 Using Notch Filters for Noise and Resonance	174
	9.1.2 Filters in the Power Converter	175
	9.1.3 Filters in the Feedback	175
	9.2 Filter Passband	175
	9.2.1 Low-Pass Filters	176
	9.2.1.1 First-Order Low-Pass Filters	176
	9.2.1.2 Second-Order Low-Pass Filters	176
	9.2.1.3 A Simple Model for a Closed Loop System	178
	9.2.1.4 Higher-Order Low-Pass Filters	178
	9.2.1.5 Butterworth Low-Pass Filters	178
	9.2.2 Notch	180
	9.2.3 Experiment 9A: Analog Filters	182
	9.2.4 Bi-Quad Filters	182
	9.3 Implementation of Filters	183
	9.3.1 Passive Analog Filters	184
	9.3.2 Active Analog Filters	184

CONTENTS

9.3.3	Switched Capacitor Filters	184
9.3.4	IIR Digital Filters	185
9.3.4.1	First-Order Low-Pass IIR Filter	185
9.3.4.2	Second-Order IIR Filter	186
9.3.4.3	Experiment 9C: Digital Filters	186
9.3.4.4	Higher-Order Digital Filters	187
9.3.5	FIR Digital Filters	187
9.4	Questions	188
Chapter 10	Introduction to Observers in Control Systems	191
10.1	Overview of Observers	191
10.1.1	Observer Terminology	192
10.1.2	Building the Luenberger Observer	193
10.1.2.1	Two Ways to Avoid $G_s(S) \neq 1$	194
10.1.2.2	Simulating the Plant and Sensor in Real Time	195
10.1.2.3	Adding the Observer Compensator	196
10.2	Experiments 10A–10C: Enhancing Stability with an Observer	196
10.2.1	Experiment 10D: Elimination of Phase Lag	200
10.3	Filter Form of the Luenberger Observer	201
10.3.1	Low-Pass and High-Pass Filtering	203
10.3.2	Block Diagram of the Filter Form	204
10.3.3	Comparing the Loop and Filter Forms	204
10.4	Designing a Luenberger Observer	205
10.4.1	Designing the Sensor Estimator	206
10.4.1.1	Sensor Scaling Gain	206
10.4.2	Sensor Filtering	207
10.4.3	Designing the Plant Estimator	207
10.4.3.1	Plant Scaling Gain (K)	208
10.4.3.2	Order of Integration	209
10.4.3.3	Filtering Effects	209
10.4.3.4	Experiment 10E: Determining the Gain Experimentally	209
10.4.4	Designing the Observer Compensator	211
10.5	Introduction to Tuning an Observer Compensator	211
10.5.1	Step 1: Temporarily Configure the Observer for Tuning	213
10.5.2	Step 2: Adjust the Observer Compensator for Stability	214
10.5.2.1	Modifying the Tuning Process for Nonconfigurable Observers	214
10.5.2.2	Tuning the Observer Compensator Analytically	215
10.5.2.3	Frequency Response of Experiment 10G	215

10.5.3	Step 3: Restore the Observer to the Normal Luenberger Configuration	217
10.6	Questions	217
Section II	Modeling	219
Chapter 11	Introduction to Modeling	221
11.1	What Is a Model?	221
11.2	Frequency-Domain Modeling	222
11.2.1	How the Frequency Domain Works	222
11.3	Time-Domain Modeling	224
11.3.1	State Variables	224
11.3.1.1	Reducing Multiple-Order Equations	224
11.3.1.2	Matrix Equations	225
11.3.1.3	Time-Based Simulation	226
11.3.2	The Modeling Environment	226
11.3.2.1	The Differential Equation Solver	226
11.3.2.2	Advanced Differential Equation Solvers	228
11.3.2.3	Selecting ΔT	228
11.3.3	The Model	229
11.3.3.1	Initial Conditions	229
11.3.3.2	Writing the Modeling Equations	230
11.3.3.3	Modeling an RC Circuit	230
11.3.3.4	Modeling a Two-Pole Low-Pass Filter	231
11.3.3.5	Modeling an Analog PI Controller	232
11.3.3.6	Modeling a Digital PI Controller	234
11.3.3.7	Adding Calculation Delay	236
11.3.3.8	Adding Saturation	236
11.3.4	Frequency Information from Time-Domain Models	237
11.4	Questions	238
Chapter 12	Nonlinear Behavior and Time Variation	239
12.1	LTI Versus non-LTI	239
12.2	Non-LTI Behavior	240
12.2.1	Slow Variation	240
12.2.2	Fast Variation	241
12.3	Dealing with Nonlinear Behavior	242
12.3.1	Modify the Plant	242
12.3.2	Tuning for Worst Case	243
12.3.3	Gain Scheduling	243
12.4	Ten Examples of Nonlinear Behavior	245
12.4.1	Plant Saturation	245

CONTENTS

12.4.2	Deadband	246
12.4.3	Reversal Shift	248
12.4.4	Variation of Apparent Inertia	249
12.4.5	Friction	250
12.4.5.1	Compensating for Friction	253
12.4.6	Quantization	254
12.4.7	Deterministic Feedback Error	254
12.4.8	Power Converter Saturation	255
12.4.9	Pulse Modulation	258
12.4.10	Hysteresis Controllers	260
12.5	Questions	261
Chapter 13	Seven Steps to Developing a Model	263
13.1	Determine the Purpose of the Model	263
13.1.1	Training	264
13.1.2	Troubleshooting	264
13.1.3	Testing	264
13.1.4	Predicting	265
13.2	Model in SI Units	265
13.3	Identify the System	266
13.3.1	Identifying the Plant	266
13.3.2	Identifying the Power Converter	267
13.3.3	Identifying the Feedback	269
13.3.4	Identifying the Controller	269
13.4	Build the Block Diagram	269
13.5	Select Frequency or Time Domain	270
13.6	Write the Model Equations	270
13.7	Verify the Model	270
Section III	Motion Control	273
Chapter 14	Encoders and Resolvers	275
14.1	Accuracy, Resolution, and Response	277
14.2	Encoders	277
14.3	Resolvers	278
14.3.1	Converting Resolver Signals	278
14.3.2	Software Resolver-to-Digital Converters	281
14.3.3	Resolver Error and Multispeed Resolvers	282
14.4	Position Resolution, Velocity Estimation, and Noise	283
14.4.1	Experiment 14A: Resolution Noise	284
14.4.2	Higher Gain Generates More Noise	285
14.4.3	Filtering the Noise	286

14.5	Alternatives for Increasing Resolution	287
14.5.1	The $1/T$ Interpolation, or Clock Pulse Counting Method	287
14.5.2	Sine Encoders	288
14.6	Cyclic Error and Torque/Velocity Ripple	289
14.6.1	Velocity Ripple	292
14.6.2	Torque Ripple	292
14.7	Experiment 14B: Cyclical Errors and Torque Ripple	294
14.7.1	Relationship Between Error Magnitude and Ripple	295
14.7.2	Relationship Between Velocity and Ripple	295
14.7.3	Relationship Between Bandwidth and Ripple	296
14.7.4	Relationship Between Inertia and Ripple	296
14.7.5	Effect of Changing the Error Harmonic	296
14.7.6	Effect of Raising Resolver Speed	296
14.7.7	Relationship Between Ripple in the Actual and Feedback Velocities	297
14.8	Choosing a Feedback Device	298
14.8.1	Suppliers	299
14.9	Questions	300
Chapter 15	Basics of the Electric Servomotor and Drive	303
15.1	Definition of a Drive	304
15.2	Definition of a Servo System	305
15.3	Basic Magnetism	305
15.3.1	Electromagnetism	307
15.3.2	The Right-Hand Rule	308
15.3.3	Completing the Magnetic Path	308
15.4	Electric Servomotors	310
15.4.1	Torque Ratings	310
15.4.2	Rotary and Linear Motion	311
15.4.3	Linear Motors	312
15.5	Permanent-Magnet (PM) Brush Motors	313
15.5.1	Creating the Winding Flux	314
15.5.2	Commutation	314
15.5.3	Torque Production	315
15.5.4	Electrical Angle Versus Mechanical Angle	315
15.5.5	K_T , the Motor Torque Constant	316
15.5.6	Motor Electrical Model	317
15.5.7	Control of PM Brush Motors	318
15.5.7.1	Current Controller	319
15.5.7.2	Voltage Modulation	320
15.5.8	Brush Motor Strengths and Weaknesses	321
15.6	Brushless PM Motors	322
15.6.1	Windings of Brushless PM Motors	323

CONTENTS

15.6.2	Sinusoidal Commutation	324
15.6.3	Phase Control of Brushless PM Motors	324
15.6.3.1	Modulation	326
15.6.3.2	Angle Advance	326
15.6.3.3	Angle Advance for Current-Loop Phase Lag	327
15.6.3.4	Field Weakening	327
15.6.3.5	Reluctance Torque	328
15.6.4	DQ Control of Brushless PM Motors	330
15.6.4.1	Modulation in DQ Control	333
15.6.4.2	Field Weakening DQ Control	333
15.6.5	Magnetic Equations for DQ	333
15.6.6	Comparing DQ and Phase Control	334
15.7	Six-Step Control of Brushless PM Motor	335
15.7.1	Sensing Position for Commutation	336
15.7.2	Comparison of Brush and Brushless Motors	337
15.8	Induction and Reluctance Motors	337
15.9	Questions	339
Chapter 16	Compliance and Resonance	341
16.1	Equations of Resonance	343
16.1.1	Resonance with Load Feedback	344
16.2	Tuned Resonance vs. Inertial-Reduction Instability	345
16.2.1	Tuned Resonance	345
16.2.2	Inertial-Reduction Instability	348
16.2.3	Experiments 16A and 16B	350
16.3	Curing Resonance	350
16.3.1	Increase Motor Inertia/Load Inertia Ratio	352
16.3.2	Stiffen the Transmission	354
16.3.3	Increase Damping	357
16.3.4	Filters	358
16.3.4.1	First-Order Filters	358
16.3.4.2	Second-Order Filters	360
16.4	Questions	360
Chapter 17	Position-Control Loops	363
17.1	P/PI Position Control	363
17.1.1	P/PI Transfer Function	365
17.1.2	Tuning the P/PI Loop	366
17.1.2.1	Tuning the PI Velocity Loop	366
17.1.2.2	Tuning the P Position Loop	367
17.1.3	Feed-Forward in P/PI Loops	368
17.1.4	Tuning P/PI Loops with Velocity Feed-Forward	370

17.1.5	Acceleration Feed-Forward in P/PI Loops	371
17.1.6	Tuning P/PI Loops with Acc/Vel Feed-Forward	372
17.2	PI/P Position Control	374
17.2.1	Tuning PI/P Loops	374
17.3	PID Position Control	375
17.3.1	Tuning the PID Position Controller	376
17.3.1.1	Selective Zeroing of the PID Integral Term	376
17.3.2	Velocity Feed-Forward and the PID Position Controller	378
17.3.3	Acceleration Feed-Forward and the PID Position Controller	379
17.3.4	Command and Disturbance Response for PID Position Loops	379
17.4	Comparison of Position Loops	380
17.4.1	Positioning, Velocity, and Current Drive Configurations	381
17.4.2	Comparison Table	383
17.4.3	Dual-Loop Position Control	383
17.5	Bode Plots for Positioning Systems	384
17.5.1	Bode Plots for Systems Using Velocity Drives	385
17.5.2	Bode Plots for Systems Using Current Drives	386
17.6	Questions	387
Chapter 18	Using the Luenberger Observer in Motion Control	389
18.1	Applications Likely to Benefit from Observers	389
18.1.1	Performance Requirements	390
18.1.2	Available Computational Resources	390
18.1.3	Controls Expertise in the User Base	390
18.1.4	Sensor Noise	390
18.1.5	Phase Lag in Motion-Control Sensors	391
18.2	Observing Velocity to Reduce Phase Lag	391
18.2.1	Eliminate Phase Lag from Simple Differences	391
18.2.1.1	Form of Observer	391
18.2.1.2	Experiment 18A: Removal of Phase Lag from Simple Differences	392
18.2.1.3	Experiment 18B: Tuning the Observer	396
18.2.2	Eliminate Phase Lag from Conversion	400
18.2.2.1	Experiment 18C: Verifying the Reduction of Conversion Delay	401
18.2.2.2	Experiment 18D: Tuning the Observer in the R-D–Based System	403

CONTENTS

18.3	Acceleration Feedback	406
18.3.1	Using Observed Acceleration	408
18.3.2	Experiment 18E: Using Observed Acceleration Feedback	408
18.4	Questions	410
Appendix A	Active Analog Implementation of Controller Elements	413
	Integrator	413
	Differentiator	414
	Lag Compensator	414
	Lead Compensator	415
	Lead-Lag Compensator	416
	Sallen-and-Key Low-Pass Filter	416
	Adjustable Notch Filter	417
Appendix B	European Symbols for Block Diagrams	419
	Part I. Linear Functions	419
	Part II. Nonlinear Functions	420
Appendix C	The Runge–Kutta Method	423
	The Runge–Kutta Algorithm	423
	Basic Version of the Runge–Kutta Algorithm	424
	C Programming Language Version of the Runge–Kutta Algorithm	426
	H-File for C Programming Language Version	427
Appendix D	Development of the Bilinear Transformation	429
	Bilinear Transformation	429
	Prewarping	429
	Factoring Polynomials	430
	Phase Advancing	431
Appendix E	The Parallel Form of Digital Algorithms	433
Appendix F	Basic Matrix Math	437
	Matrix Summation	437
	Matrix Multiplication	437
	Matrix Scaling	438
	Matrix Inversion	438
Appendix G	Answers to End-of-Chapter Questions	439
	Chapter 2	439
	Chapter 3	439
	Chapter 4	440
	Chapter 5	440
	Chapter 6	441

CONTENTS

Chapter 7	441
Chapter 8	442
Chapter 9	442
Chapter 10	443
Chapter 11	443
Chapter 12	445
Chapter 14	445
Chapter 15	446
Chapter 16	447
Chapter 17	448
Chapter 18	448
Index	451