

Contents

1	Introduction to Linear Feedback Controls	1
1.1	What are Feedback Control Systems?	4
1.2	Some Terminology	6
1.3	Design of Feedback Control Systems	8
1.4	Two-Point Control	10
2	Systems and Signals	15
2.1	Example First-Order System: The RC-Lowpass	17
2.2	Example Second-Order System: The Spring-Mass-Damper System .	19
2.3	Obtaining the System Response from a Step Input	20
2.4	State-Space Models	22
2.5	Systems and Signals in Scilab	24
3	Solving Differential Equations in the Laplace Domain	27
3.1	The Laplace Transform	27
3.2	Fourier Series and the Fourier Transform	32
3.3	Representation of the RC Lowpass and Spring-Mass-Damper Systems in the Laplace Domain	37
3.4	Transient and Steady-State Response	41
3.5	Partial Fraction Expansion	45
3.5.1	Partial Fraction Expansion Examples	47
3.5.2	Partial Fraction Expansion in Scilab	51
3.6	Building Blocks of Linear Systems	52
3.6.1	Gain Blocks	52
3.6.2	Differentiators	53
3.6.3	Integrators	53
3.6.4	Phase-Lag System, First-Order Lowpass	54
3.6.5	First-Order Highpass	54
3.6.6	PD System or Phase-Lead Compensator	55
3.6.7	Allpass Compensator	56
3.6.8	Second-Order System	56

	3.6.9	Dead-Time System (Time-Delay System)	57
4		Time-Discrete Systems	59
	4.1	Analog-to-Digital Conversion and the Zero-Order Hold	60
	4.2	The z -Transform	63
	4.3	The Relationship between Laplace- and z -domains	68
	4.4	The w -Transform	72
	4.5	Building Blocks for Digital Controllers	73
	4.5.1	Gain Block	74
	4.5.2	Differentiator	75
	4.5.3	Integrator	75
	4.5.4	PID Controller	76
	4.5.5	Time-Lag System	77
	4.5.6	Time-Lead System	78
	4.5.7	Lead-Lag Compensator	78
5		First Comprehensive Example:	
		The Temperature-Controlled Waterbath	81
	5.1	Mathematical Model of the Process	82
	5.2	Determination of the System Coefficients	83
	5.3	Determining the Transfer Function – General Remarks	87
	5.4	Introducing Feedback Control	88
	5.5	Comparison of the Open-Loop and Closed-Loop Systems	90
6		Laplace- and z-Domain Description of the Waterbath Example	93
	6.1	Laplace-Domain Description of the Process	93
	6.2	The Closed-Loop System	96
	6.3	Sensitivity and Tracking Error	97
	6.4	Using a PI-Controller	99
	6.5	Time-Discrete Control	103
	6.5.1	Time-Discrete Control with the Bilinear Transform	105
7		Block Diagrams:	
		Formal Graphical Description of Linear Systems	107
	7.1	Symbols of a Block Diagram	107
	7.2	Block Diagram Manipulation	108
	7.3	Block Diagram Simplification Examples	111
	7.4	Signal Flow Graphs	115
8		Linearization of Nonlinear Components	119
	8.1	Linearization of Components with Analytical Description	120
	8.2	Linearization of Tabular Data	122
	8.3	Linearization of Components with Graphical Data	124
	8.4	Saturation Effects	124

9	A Tale of Two Poles: The Positioner Example and the Significance of the Poles in the s-Plane	127
9.1	A Head-Positioning System	128
9.2	Introducing Feedback Control	129
9.3	Dynamic Response of the Closed-Loop System	131
9.4	Dynamic Response Performance Metrics	134
9.5	Time-Integrated Performance Metrics	137
9.6	Feedback Control with a Time-Discrete Controller	140
10	Stability Analysis for Linear Systems	145
10.1	The Routh-Hurwitz Scheme	146
10.2	Routh Arrays for Low-Order Systems	148
10.3	Stability of Time-Discrete Systems with the w -Transform	150
10.4	The Jury Test	150
10.5	Jury Arrays for Low-Order Systems	151
10.6	Example Applications	153
11	Frequency-Domain Analysis and Design Methods	157
11.1	Frequency Response of LTI Systems	157
11.2	Frequency Response and Stability	160
11.3	Bode Plots	161
11.4	Definition of Phase and Gain Margin	161
11.5	Construction of Bode Diagrams	164
11.6	Frequency Response of a Second-Order System	166
11.7	Frequency Response of Digital Filters	170
11.8	The Nyquist Stability Criterion	173
11.8.1	The Nyquist Stability Criterion for Time-Discrete Systems ..	179
11.8.2	Nyquist Stability in Scilab	181
12	The Root Locus Method	183
12.1	Graphical Construction of Root Locus Plots	184
12.1.1	Prepare the Characteristic Equation in Root-Locus Form ...	185
12.1.2	Open-Loop Poles and Zeros, and Asymptotes	186
12.1.3	Branches of the Root Locus on the Real Axis	187
12.1.4	Branch-off Points	188
12.1.5	Departure Angles for Complex Poles	189
12.2	Root-Locus Diagrams in Scilab	189
12.3	Design Example: Positioner with PI Control	191
12.4	Design Example: Resonance Reduction	194
12.5	The Root Locus Method for Time-Discrete Systems	198

13 The PID Controller	201
13.1 Intuitive Introduction	201
13.2 Transfer Functions with PID Control	202
13.2.1 PID control of a First-Order Process	203
13.2.2 PID control of a Second-Order Process	204
13.3 Frequency-Domain Aspects of PID Control	207
13.4 Time-Discrete PID Controllers	208
13.5 PID Controller Tuning	212
13.5.1 Iterative Adjustment With an Oscilloscope	212
13.5.2 Ziegler-Nichols Tuning Method	214
13.5.3 Cohen-Coon Tuning Method	215
13.6 Variations and Alternatives of PID Control	215
13.6.1 Integral Windup	215
13.6.2 Nonlinear Processes	216
13.6.3 Pole Cancellation	216
13.7 Conclusion	217
14 Design Examples	219
14.1 Precision Temperature Control	219
14.2 Fast-Tracking Temperature Control	222
14.3 Motor Speed and Position Control	225
14.3.1 Open-Loop Control with Step Motors	225
14.3.2 Closed-Loop Control with DC Motors	228
14.4 Resonant Sine Oscillator	232
14.5 Low-Distortion (HiFi) Amplifiers with Feedback	240
14.6 Phase-Locked Loop Systems	245
14.7 Stabilizing an Unstable System	250
Laplace Correspondence Tables	259
Z-Transform Correspondence Tables	265
Introduction to Operational Amplifiers	269
Relevant Scilab Commands	275
References and Further Reading	277
Glossary	279