
CONTENTS

Preface	xix
1 Introduction	1
1.1 Introduction	1
1.2 Digital Control-System Modeling	2
1.2.1 Sampling Process	2
1.2.2 System Terminology	4
1.2.3 General Sampled-Data System Variables	5
1.2.4 Systems Modeling	7
1.3 Why Use Digital Control?	11
1.4 Control-System Analysis and Synthesis	12
1.5 The Interdisciplinary Field of Digital Control	13
1.6 Digital Control Development	14
1.7 Nature of the Engineering Control Problem	16
1.8 Text Outline	17
1.9 Summary	18
2 Continuous-Time Control-System Response Characteristics	19
2.1 Introduction	19
2.2 Background	20
2.3 Simple Second-Order System Tracking-Response Characteristics	23
2.4 Higher-Order System Tracking-Response Characteristics	27
2.4.1 Time-Response Characteristics of a Third-Order All-Pole Plant	28
2.4.2 Time-Response Characteristics of a Third-Order, One-Zero Plant	28
2.4.3 Time-Response Characteristics of a Sixth-Order Plant	31
2.4.4 Correlation between Frequency and Time Domains	32

2.4.5	Correlation of the Control Ratio with Frequency and Time Responses	34
2.5	Nichol's Chart (NC) Analysis	37
2.6	Cascade-Compensator Design Procedures	39
2.7	Synthesizing a Desired Tracking Control Ratio with a Unit-Step Input	43
2.8	Feedback Compensation	49
2.9	Disturbance Rejection	51
2.9.1	Second-order Disturbance-Rejection Model	51
2.9.2	Single-Input Single-Output (SISO) Design Principles for Disturbance Rejection	55
2.9.3	Examples	56
2.10	Summary	62
3	Linear Systems and the Sampling Process	63
3.1	Introduction	63
3.2	Linear Time-Invariant (LTI) System	63
3.3	Solution of Linear Difference Equations	68
3.4	Sampling Process (Frequency Domain Analysis)	73
3.5	Ideal Sampler	77
3.6	Shannon's Sampling Theorem	83
3.7	Sampling-Time Selection	84
3.7.1	Single-Rate Sampling	85
3.7.2	Multirate Sampling	85
3.8	Weighting Sequence	86
3.9	Data Conversion Introduction	94
3.9.1	Zero-Order Hold (ZOH)	94
3.10	Summary	98
4	Discrete Systems Modeling	99
4.1	Introduction	99
4.2	Definition and Determination of the z -Plane Transform \mathcal{Z}	100
4.3	Mapping between s and z Domains	111
4.3.1	Mapping of the Primary Strip	112
4.3.2	Mapping of the Constant Frequency Loci	114
4.3.3	Mapping of the Constant Damping-Coefficient Loci	114
4.3.4	Mapping of the Constant Damping-Ratio Loci	115
4.4	\mathcal{Z} -Transform Theorems	118
4.5	The Inverse \mathcal{Z} -Transform, \mathcal{Z}^{-1}	123
4.5.1	Partial-Fraction Method	124
4.5.2	Power-Series Method (Direct Division Method)	128
4.6	Limitations	130
4.7	\mathcal{Z} Transform of System Equations	131
4.7.1	Open-Loop Hybrid Sampled-Data Control System	131
4.7.2	Open-Loop Discrete-Input-Data Control System	136
4.7.3	Closed-Loop Sampled-Data Control System	137
4.7.4	Signal Flow Graphs for Hybrid Systems (HSFG)	140
4.8	Digital-Computer Transfer Function	145
4.9	Summary	149

5	Discrete Control Analysis	151
5.1	Introduction	151
5.2	System Stability	152
5.2.1	z -Plane Stability	153
5.2.2	z -Domain Nyquist Stability	155
5.2.3	Polar Plot Analysis	156
5.2.4	Extended z -Domain Stability Analysis: Jury's Stability Test	157
5.3	Steady-State Error Analysis for Stable Systems	160
5.3.1	Steady-State Error-Coefficient Formulation	162
5.3.2	Evaluation of Steady-State Error Coefficients	163
5.3.3	Use of Steady-State Error Coefficients	164
5.4	Root-Locus Analysis	166
5.4.1	Procedure Outline	167
5.4.2	Root-Locus Construction Rules for Negative Feedback	168
5.4.3	Examples	170
5.5	Bilinear Transformations	176
5.5.1	s -Plane and w -Plane Relationship	177
5.5.2	Routh Stability Criterion in w -Plane	180
5.6	Time-Response Correlation between Planes (s , z , and w)	183
5.7	Frequency Response	188
5.8	Summary	194
6	Discrete Transform Analysis (Approximations)	198
6.1	Introduction	198
6.2	Folding or Aliasing	200
6.3	Transformation Methods between Planes (s , z , and w)	201
6.4	Mapping Approximations of \mathcal{Z} -Transform (Or Numerical Solution of Differential Equations)	206
6.4.1	First-Backward Difference	206
6.4.2	Tustin Transformation	209
6.5	Pseudo-Continuous-Time (PCT) Control System	213
6.6	Analysis of a Basic (Uncompensated) System	215
6.6.1	PCT Control System Model	215
6.6.2	Sampled-Data Control System	216
6.7	Summary	219
7	Principles of Signal Conversion and Measurement	220
7.1	Introduction	220
7.2	Timing Considerations	220
7.3	Binary Coding of Information	222
7.4	Conversion Systems	224
7.5	Digital-to-Analog (D/A) Conversion Structures	225
7.6	General Analog-to-Digital (A/D) Conversion Structures	229
7.7	Specific Analog to Digital Conversion Systems	234
7.8	Measures of Converter Performance	243
7.9	Sample-and-Hold Operation	245
7.10	Multiplexing	247
7.11	Integrated A/D and D/A Interfaces	248

7.12	Measurement in Digital Control Systems	250
7.12.1	Temperature Measurements	250
7.12.2	Pressure and Related Measurements	253
7.12.3	Motion Measurement	256
7.12.4	Position Measurement	258
7.12.5	Transducer Signal Conditioning	260
7.12.6	Saturation Analysis	260
7.13	Programming Input and Output (I/O)	260
7.13.1	I/O Hardware Structure	261
7.13.2	Programmed I/O Mode	261
7.13.3	Interrupt I/O Devices	263
7.14	Summary	265
8	Digital-Control-System Implementation	267
8.1	Introduction	267
8.2	Control Logic	268
8.3	Computer Architecture for Control	271
8.4	Software for Control	274
8.4.1	Algorithms	274
8.4.2	Language Hierarchy	277
8.5	Software Engineering in Digital Control Systems	278
8.6	Requirements—Data Flow Diagrams (DFDs)	281
8.7	Real-Time Design for Digital Control	285
8.8	Software Design in Control Systems	289
8.9	Direct Design Method	292
8.10	Structured Programming and Implementation	293
8.11	Software Testing	293
8.12	Real-Time Scheduling	295
8.13	Real-Time Operating Systems for Digital Control	299
8.13.1	Real-Time Operating Systems Requirements	301
8.13.2	Simple Real-Time Operating System	302
8.14	Watchdog Timers	304
8.15	Sampling-Time Selection	305
8.15.1	Single-Rate Sampling	306
8.15.2	Multirate Sampling	307
8.16	User Interfaces to Real-Time Operating Systems	308
8.17	Summary	309
9	Random Processes in Digital Control Systems	311
9.1	Introduction	311
9.2	Digital Control of Random Inputs	312
9.3	Random Processes (Stochastic Processes)	313
9.4	Random Process Time Averages	317
9.5	Linear System Response to Random Signals	319
9.5.1	Convolution Model	319
9.5.2	Difference Equation Model	322
9.5.3	Spectral Density of Linear Discrete Systems	324
9.6	Vector-Matrix Representation of Random Processes	326

9.7	Summary	329
10	Finite Word Length and Compensator Structure	330
10.1	Introduction	330
10.2	Quantization Errors	331
10.3	Compensator Structure and Arithmetic Errors	341
10.4	Compensator Coefficient Representation	348
10.5	Sensitivity of Coefficients	352
10.6	Scaling	356
10.7	Limit-Cycle Phenomenon Due to Quantization	358
10.8	Simulation and Tuning	367
10.9	Detailed Design/Implementation Process	368
10.10	Summary	369
11	Cascade Compensation—Digitization (DIG) Technique	370
11.1	Introduction	370
11.2	Digitization (DIG) Design Technique	372
11.3	Guillemin–Truxal (GT) Compensation Method	374
11.4	Lead Cascade Compensation	379
11.4.1	<i>s</i> -Plane DIG Design	379
11.4.2	<i>w</i> -Plane DIG Design	381
11.4.3	<i>s</i> -Plane to <i>w</i> -Plane Correlation	384
11.5	Lag Compensation	385
11.6	Lag-Lead Compensation	385
11.7	Extensive Cascade DIG Example	387
11.7.1	Analysis of the Basic System	387
11.7.2	Guillemin–Truxal Approach	388
11.7.3	Pseudo-Continuous Time (PCT) Approach	389
11.7.4	<i>w</i> -Domain DIG Design	391
11.8	Summary	392
12	Cascade Compensation—Direct (DIR) Technique	394
12.1	Introduction	394
12.2	Direct (DIR) Design Technique	394
12.3	Lead Compensation (DIR)	396
12.4	Lag Compensation (DIR)	397
12.5	Lag-Lead Compensation—DIR	400
12.6	Frequency-Response Characteristics	400
12.7	Proportional Integral Derivative (PID) Controller	404
12.8	Set-Point PID Controllers	406
12.9	Extensive Cascade Example (DIR)	408
12.9.1	Lead Compensation	408
12.9.2	Lag Compensation	409
12.9.3	Controller Implementation	410
12.10	Deadbeat Response	411
12.11	Summary	412

13	Feedback Compensation	413
13.1	Introduction	413
13.2	General Analysis	414
13.3	DIR Technique for Feedback Control	417
	13.3.1 Guillemin–Truxal Approach	417
	13.3.2 Root-Locus Approach	420
13.4	DIG Technique for Feedback Control	421
13.5	Controlling Unwanted Disturbances	424
	13.5.1 DIG Technique	425
	13.5.2 DIR Technique	428
13.6	Extensive Digital Feedback Compensator Example	428
	13.6.1 DIG Example	429
	13.6.2 DIR Example	430
13.7	Software for Digital Controllers	431
13.8	Summary	435
14	Discrete State-Variable Model	436
14.1	Introduction	436
14.2	State-Variable Representation	437
14.3	Time-Domain State and Output Equations for Sampled-Data Control Systems	443
14.4	State-Variable Representation of a Discrete-Time SISO System	448
	14.4.1 Phase-Variable Method	448
	14.4.2 Canonical-Variable Method	453
	14.4.3 Physical-Variable Method	459
	14.4.4 State Transition Equation	462
	14.4.5 State-Variable Representation Summary	464
14.5	State-Variable Representation in the z Domain	464
14.6	System Stability	471
14.7	Time Response between Sampling Instants	474
14.8	Summary	476
15	State-Space Design Methods	477
15.1	Introduction	477
15.2	State-Feedback Pole Placement	477
15.3	State-Variable Feedback: Parameter Insensitivity	479
15.4	State Feedback Using Digitization	479
15.5	State-Feedback H -Equivalent Digital Control System	483
15.6	Design Procedure	486
15.7	Frequency-Domain Compensation Design Using Mean-Square Error Minimization	490
15.8	Digital Filters	493
15.9	Direct s -Plane to w -Plane Transformation	499
	15.9.1 Scalar Case Relationship	500
	15.9.2 Vector-Matrix Formulation	502
	15.9.3 Accuracy Considerations of the w Transformation	503
	15.9.4 Model Relationship as $T \rightarrow$ Zero	505
	15.9.5 Normal Form	506
15.10	Summary	506

16	Discrete Quantitative Feedback Technique	508
16.1	Introduction	508
16.2	Continuous MISO and MIMO QFT Approach	509
16.3	Non-Minimum-Phase Analog Plant	513
	16.3.1 Analog QFT Design Procedure for an nmp Plant	514
16.4	Discrete MISO Model with Plant Uncertainty	517
16.5	QFT w -Domain DIG Design	518
	16.5.1 Closed-Loop System Specifications	520
	16.5.2 Plant Templates	523
	16.5.3 Bounds $B(jv)$ on $L_o(jv)$	524
	16.5.4 Nonminimum-Phase $L_o(w)$	524
	16.5.5 Synthesizing $L_{mo}(w)$	527
	16.5.6 $\omega_s = 120$ Is Too Small	528
	16.5.7 Error in the Design	532
	16.5.8 Design of the Prefilter $F(w)$	535
16.6	Simulation	535
16.7	Basic Design Procedure for a MISO Sampled-Data Control System	538
16.8	Applicability of Design Techniques to Other Plants	542
	16.8.1 MIMO Plants	542
	16.8.2 Nonlinear Plants	543
16.9	QFT Technique Applied to the PCT System	543
16.10	Summary	543
	16.10.1 Minimum-Phase, Nonminimum Phase and Unstable $P(s)$	543
	16.10.2 Disturbance Attenuation	544
	16.10.3 Conclusions	544
17	Modern Discrete Control Theory	546
17.1	Introduction	546
17.2	Basic System Structure	547
17.3	Discrete Controllability	548
17.4	State-Space Pole Placement	552
17.5	Discrete Observability	553
17.6	State Observers	557
	17.6.1 Full-State Observers	557
	17.6.2 Reduced-Order and Current Observers	561
17.7	State-Space Stability	563
17.8	Summary	563
18	Discrete Optimal Control	565
18.1	Introduction	565
18.2	Optimal Control Concepts	566
18.3	Maximum Principle	567
18.4	Discrete Linear Regulator	568
	18.4.1 General Second-Order System Optimal Controllers	574
	18.4.2 Discrete Riccati Equation Solution	575
18.5	Optimal Control Variations	580
18.6	Sampling Time	581
18.7	Summary	582

19	Discrete Estimation and Stochastic Control	583
19.1	Introduction	583
19.2	Parameter Identification	584
19.3	Discrete Optimal Estimation	590
19.3.1	Additive Noise Model	590
19.3.2	Estimation Problem Formulation	591
19.3.3	Discrete Optimal Estimation	592
19.3.4	Solution to Optimal Filter Equations	597
19.4	Discrete Stochastic Control	597
19.4.1	Combined Model	597
19.4.2	Optimal Performance	598
19.5	H_∞ Robust Optimal Control	600
19.6	Discrete Adaptive Control	603
19.7	Summary	605
	Bibliography	606
	Problems	613
	Appendixes	
A	Fourier Transform	661
B	Convolution	667
C	Padé Approximation	669
D	Power Series	672
E	Computer-Aided-Design (CAD) Programs for Control	674
F	Matrix Manipulations	678
G	Signal Flow Graphs	689
H	w -Transformation Characteristics	695
I	Number Representations	696
J	Theory of Probability	701
K	Discrete QFT Design Process	709
	Answers to Selected Problems	714
	Index	739