
CONTENTS

	Preface	xv
Chapter 1	Introduction	1
1-1	Introduction	1
1-2	Digital-Control-System Modeling	2
	A. A Sampling Process	2
	B. System Terminology	4
	C. Examples	4
	D. General Sampled-Data-System Variables	9
	E. General Modeling	11
1-3	Why Use Digital Control	11
	A. Advantages	11
	B. Disadvantages	13
1-4	Digital-Control-Systems Architecture	13
1-5	Techniques of Control-System Analysis and Synthesis	15
	A. Time Domain/Frequency Domain	15
	B. Stochastic Analysis	16
	C. Aids	16
	D. Design Approach	17
1-6	The Interdisciplinary Field of Digital Control	18
1-7	Digital Control Development	19
1-8	General Nature of the Engineering Control Problem	23
1-9	Text Outline	24
1-10	Summary	26
Chapter 2	Computer System Architecture	27
2-1	Introduction	27
2-2	Computers and Numbers	27
	A. Number Systems	28
	B. Conversion of Number Systems	31

	C. Basic Computer Arithmetic	34
	D. Binary Coding of Alphanumeric Information	37
2-3	Computer Logic and Boolean Algebra	39
	A. Logical Reasoning	40
	B. Logic Operations and Truth Tables	41
2-4	Computer Architecture	46
	A. Input-Output Devices	48
	B. Memory and Information Specification	48
	C. Manipulation Unit (Arithmetic/Logic Unit)	49
	D. Control Unit	49
	E. Operating Systems	49
	F. Application Programs	50
2-5	Signed Number Representations and Arithmetic Processes	50
	A. Representation of Signed Binary Arithmetic Numbers	50
	B. Binary Addition Algorithms	54
	C. Floating-Point Number Representation	57
2-6	Algorithms	57
2-7	Software Language Hierarchy	61
	A. Assembly Language	63
	B. Program Loaders	66
2-8	Operating Systems for Control	68
2-9	Language Selection	69
2-10	Program Development	70
2-11	Summary	72
Chapter 3	Linear Systems and the Sampling Process	73
3-1	Introduction	73
3-2	Linear Time-Invariant (LTI) System	73
3-3	Sampling Process (Frequency-Domain Analysis)	78
3-4	Ideal Sampler	82
3-5	Shannon's Sampling Theorem	87
3-6	Uniform-Rate Sampling	88
3-7	Generation and Solution of Linear Difference Equations: System Model	89
3-8	Weighting Sequence (Sampled-Data System)	96
3-9	Data Conversion Processes	103
3-10	Summary	107
Chapter 4	Discrete Systems Modeling	108
4-1	Introduction	108
4-2	Definition and Determination of the $\mathcal{Z}$ Transform	108
4-3	Mapping between s and z Domains	118
	A. Mapping of the Primary Strip	119
	B. Mapping of the Constant Frequency Loci	120
	C. Mapping of the Constant Damping-Coefficient Loci	121
	D. Mapping of the Constant Damping-Ratio Loci	121
4-4	$\mathcal{Z}$ -transform Theorems	125

4-5	The Inverse $\mathcal{Z}$ Transform, $\mathcal{Z}^{-1}$	129
	A. Partial-Fraction Method	130
	B. Power-Series Method (Direct Division Method)	135
4-6	Limitations	136
4-7	$\mathcal{Z}$ Transform of System Equations	137
	A. Open-Loop Hybrid Sampled-Data Control System	137
	B. Open-Loop Discrete-Input-Data Control System	142
	C. Closed-Loop Sampled-Data Control System	143
4-8	Digital-Computer Transfer Function	146
4-9	The Modified $\mathcal{Z}$ -transform Method	149
	A. Obtaining the Modified $\mathcal{Z}$ Transform, $\mathcal{Z}_m$	150
	B. Evaluation of $e[(k - \rho)T]$	152
	C. Modified $\mathcal{Z}$ -Transform Theorems	154
4-10	Summary	155

Chapter 5 Continuous-Time Control System Response Characteristics 156

5-1	Introduction	156
5-2	Simple Second-Order System Response Characteristics	160
5-3	Higher-Order System Response Characteristics	163
	A. Time-Response Characteristics of a Third-Order All-Pole Plant	163
	B. Time-Response Characteristics of a Sixth-Order Plant	164
	C. Correlation between Frequency and Time Domain	165
	D. Correlation of the Poles and Zeros of the Control Ratio with Frequency and Time Responses	167
	E. Effect of a Third Real Dominant Root	171
5-4	Cascade-Compensator Design Procedures	172
5-5	Synthesizing a Desired Control Ratio for a Continuous-Data Control System with a Unit-Step Input	176
5-6	Feedback Compensation	180
5-7	Disturbance Rejection	180
5-8	Summary	190

Chapter 6 Discrete Control Analysis 191

6-1	Introduction	191
6-2	z -Domain Stability	194
6-3	Extended z -Domain Stability Analysis: Jury's Stability Test	198
6-4	Steady-State Error Analysis for Stable Systems	201
	A. Steady-State Error-Coefficient Formulation	202
	B. Evaluation of Steady-State Error Coefficients	203
	C. Use of Steady-State Error Coefficients	204
6-5	Root-Locus Analysis	206
	A. Procedure Outline	207
	B. Summary of Root-Locus Construction Rules for Negative Feedback	207
	C. Examples	210

6-6	Bilinear Transformations	216
	A. s - and w -Plane Relationship	217
	B. Routh Stability Criterion in w Plane	219
6-7	s -, z -, and w -Plane Time-Response Characteristics Correlation	223
6-8	Frequency Response	226
6-9	Summary	233
Chapter 7	Discrete Transform Analysis (Approximations)	234
7-1	Introduction	234
7-2	Folding or Aliasing	236
7-3	s - to z - (or w -) Plane Transformation Methods	237
7-4	Mapping Approximations of $\mathcal{Z}$ Transform (or Numerical Solution of Differential Equations)	240
	A. First-Backward Difference	240
	B. Tustin Transformation	246
7-5	Pseudo-Continuous-Time (PCT) Control System	248
7-6	The Analysis of a Basic (Uncompensated) System	251
	A. PCT Control-System Model	251
	B. Sampled-Data Control System	252
7-7	Summary	256
Chapter 8	Principles of Signal Conversion	257
8-1	Introduction	257
8-2	Timing Considerations	257
8-3	Conversion Systems	259
8-4	General Digital-to-Analog (D/A) Conversion Structures	260
8-5	General Analog-to-Digital (A/D) Conversion Structures	264
	A. Basic Reference Technique	264
	B. Data-Transfer Organization	265
	C. Information Flow Structure	266
	D. Timing Structure	266
	E. Comparator Operation	266
	F. Digital Coding	267
	G. Scaling	268
	H. Organization Combinations	269
8-6	Analog-to-Digital Systems	269
	A. Simultaneous or Flash Method (Parallel)	271
	B. Feedback Structures (Serial)	272
	C. Counter Method (Serial)	272
	D. Continuous or Tracking Method	273
	E. Successive-Approximation Method (Serial)	276
	F. Special A/D Conversion Techniques	278
8-7	Measures of Converter Performance	279
8-8	Sample-and-Hold Operation	281
8-9	Multiplexing	283
8-10	Integrated Computer Conversion Interfaces	284

8-11	Measurement in Digital Control Systems	286
	A. Temperature Measurements	287
	B. Pressure Measurements	289
	C. Rate Measurements	290
	D. Position Measurements	292
8-12	Programming Input and Output	292
	A. I/O Hardware Structure	293
	B. Programmed I/O Mode	294
	C. Interrupt I/O Devices	296
8-13	Summary	298

Chapter 9 Random Processes 299

9-1	Introduction	299
9-2	Basic Probability	300
9-3	Random Variable Basics	303
9-4	Estimating Random Variable Parameters	309
9-5	Random Processes (Stochastic Processes)	311
9-6	Random Process Time Averages	315
9-7	Linear System Response to Random Signals	317
9-8	Summary	318

Chapter 10 Analysis of Finite Word Length 319

10-1	Introduction	319
10-2	Converter Errors	320
10-3	Arithmetic Operations	330
10-4	Compensator Coefficient Representation	336
10-5	Sensitivity of Coefficients	339
10-6	Scaling	343
10-7	Simulation	344
10-8	Limit-Cycle Phenomenon Due to Quantization	345
10-9	Summary	353

Chapter 11 Cascade Compensation 354

11-1	Introduction	354
11-2	Design Procedures	355
	A. DIG (Digitalization) Technique	355
	B. DIR (Direct) Technique	358
11-3	Guillemin-Truxal Compensation Method (DIG)	359
11-4	Lead Cascade Compensation (DIG and DIR)	364
	A. s -Plane DIG Design	364
	B. w -Plane DIG Design	367
	C. z -Plane DIR Design	369
	D. Frequency-Response Characteristics	370
11-5	Lag and Lag-Lead Compensation (DIG and DIR)	373
	A. Lag Compensation	374
	B. Lag-Lead Compensation	378
	C. PID Controller	379

11-6	Frequency-Domain Compensation Design Using Mean-Square Error Minimization	381
11-7	Digital Filters	384
11-8	Software for a Digital Controller	391
	A. Program Executive for Digital Control Systems	397
	B. Data Input	401
	C. Program Filter (Simple Second-order Filter)	402
	D. Data Output	402
	E. Important Implementation Notes	402
11-9	Deadbeat Response	403
11-10	Summary	404

Chapter 12 Feedback Compensation 406

12-1	Introduction	406
12-2	General Analysis	407
12-3	DIR Technique	410
	A. Guillemin–Truxal Approach	410
	B. Root-Locus Approach	412
12-4	DIG Technique	413
12-5	Unwanted Disturbances	417
	A. DIG Technique	417
	B. DIR Technique	420
12-6	Summary	421

Chapter 13 Software Engineering in Digital Control Systems 423

13-1	Introduction	423
13-2	Software Quality	424
13-3	Requirements Analysis	426
	A. Data Flow Diagrams (DFDs)	427
	B. Generation of DFDs	429
13-4	Software Design	433
	A. Module Coupling	435
	B. Module Cohesion	439
	C. Design Method	442
	D. Design Heuristics	447
	E. Transform Analysis	448
	F. Transaction Analysis	452
	G. Other Design Techniques	455
13-5	Structured Programming	456
	A. Program Control Structures	456
	B. Structured Programming Utilization	462
	C. Programming Style	463
13-6	Software Testing	467
	A. Testing Approaches	468
	B. Debugging	470
13-7	Summary	471

Chapter 14	Real-Time Operating Systems for Digital Control	473
14-1	Introduction	473
14-2	Real-Time Operating System Requirements	475
14-3	Input-Output Management	476
14-4	Task Scheduler	477
14-5	Storage Management	479
14-6	Some Examples of Real-Time Operating Systems	482
	A. Simple Real-Time Operating System	482
	B. Extended Real-Time Operating System	484
	C. Real-Time Operating System with I/O Interrupts	485
	D. Real-Time Operating System with Secondary Storage	486
	E. Real-Time Operating System with Memory Partitions	490
	F. Other Real-Time Operating Systems	492
14-7	Common Resource Access	492
14-8	Watchdog Timers	496
14-9	Sampling-Time Selection	496
	A. Single-Rate Sampling	498
	B. Multirate Sampling	499
14-10	User Interfaces to Real-Time Operating Systems	500
14-11	Summary	501
Chapter 15	Introduction to Discrete State-Variable Model	503
15-1	Introduction	503
15-2	State-Variable Representation of Continuous-Data Control Systems	504
15-3	Time-Domain State and Output Equations for Sampled-Data Control Systems	511
15-4	State-Variable Representation in the Time Domain of a Discrete-Time SISO System	515
	A. Phase-Variable Method	516
	B. Canonical-Variable Method	522
	C. Physical-Variable Method	529
	D. State Transition Equation	532
	E. SV Representation Summary	533
15-5	State-Variable Representation of a Sampled-Data Control System in the z Domain	534
15-6	System Stability	541
15-7	Time Response in between Sampling Instants	545
15-8	State-Variable Feedback: Parameter Insensitivity	547
	A. State-Feedback Continuous-Time Control System	547
	B. State-Feedback H -Equivalent Digital Control System	551
	C. Design Procedure	554
15-9	Summary	557
	Bibliography	559

Problems	564
Appendixes	603
A Fourier Transform	603
B Convolution	609
C Padé Approximations	611
D Power Series	615
E Interactive Computer-Aided-Design (CAD) Programs for Digital and Continuous Control-System Analysis and Synthesis	617
F PDP-11/LSI-11 Assembly Language	624
Answers to Selected Problems	632
Index	655