CONTENTS

Universidad Nacional de Entre Ríos
Facultad de Ingeniería

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 $\mathscr{Z}$ 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	$\mathscr{Z}$-transform Theorems	125

4-5 The Inverse $\mathscr{Z}$ Transform, $\mathscr{Z}^{-1}$ 129
A. Partial-Fraction Method 130
B. Power-Series Method (Direct Divison Method) 135
4-6 Limitations 136
4-7 $\mathscr{Z}$ 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 $\mathscr{Z}$-transform Method 149
A. Obtaining the Modified $\mathscr{Z}$ Transform, $\mathscr{Z}_m$ 150
B. Evaluation of $e[(k-\rho)T]$ 152
C. Modified $\mathscr{Z}$-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 $\mathscr{Z}$ 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 Contol-System Analysis and Synthesis 617
F PDP-11/LSI-11 Assembly Language 624

Answers to Selected Problems 632
Index 655