# Digital Control System Analysis & Design, Global Edition

## Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover</td>
<td></td>
</tr>
<tr>
<td>Dedication</td>
<td></td>
</tr>
<tr>
<td>Contents</td>
<td></td>
</tr>
<tr>
<td>Preface</td>
<td></td>
</tr>
<tr>
<td>Chapter 1: Introduction</td>
<td></td>
</tr>
<tr>
<td>1.1 Overview</td>
<td></td>
</tr>
<tr>
<td>1.2 Digital Control System</td>
<td></td>
</tr>
<tr>
<td>1.3 The Control Problem</td>
<td></td>
</tr>
<tr>
<td>1.4 Satellite Model</td>
<td></td>
</tr>
<tr>
<td>1.5 Servomotor System Model</td>
<td></td>
</tr>
<tr>
<td>Antenna Pointing System</td>
<td></td>
</tr>
<tr>
<td>Robotic Control System</td>
<td></td>
</tr>
<tr>
<td>1.6 Temperature Control System</td>
<td></td>
</tr>
<tr>
<td>1.7 Single-Machine Infinite Bus Power System</td>
<td></td>
</tr>
<tr>
<td>1.8 Summary</td>
<td></td>
</tr>
<tr>
<td>References</td>
<td></td>
</tr>
<tr>
<td>Problems</td>
<td></td>
</tr>
<tr>
<td>Chapter 2: Discrete-Time Systems and the z-Transform</td>
<td></td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td></td>
</tr>
<tr>
<td>2.2 Discrete-Time Systems</td>
<td></td>
</tr>
<tr>
<td>2.3 Transform Methods</td>
<td></td>
</tr>
<tr>
<td>2.4 Properties of the z-Transform</td>
<td></td>
</tr>
<tr>
<td>Addition and Subtraction</td>
<td></td>
</tr>
<tr>
<td>Multiplication by a Constant</td>
<td></td>
</tr>
<tr>
<td>Real Translation</td>
<td></td>
</tr>
<tr>
<td>Complex Translation</td>
<td></td>
</tr>
<tr>
<td>Initial Value</td>
<td></td>
</tr>
<tr>
<td>Final Value</td>
<td></td>
</tr>
<tr>
<td>2.5 Finding z-Transforms</td>
<td></td>
</tr>
<tr>
<td>2.6 Solution of Difference Equations</td>
<td></td>
</tr>
<tr>
<td>2.7 The Inverse z-Transform</td>
<td></td>
</tr>
<tr>
<td>Power Series Method</td>
<td></td>
</tr>
<tr>
<td>Partial-Fraction Expansion Method</td>
<td></td>
</tr>
<tr>
<td>Inversion-Formula Method</td>
<td></td>
</tr>
<tr>
<td>Discrete Convolution</td>
<td></td>
</tr>
</tbody>
</table>
Table of Contents

2.8 Simulation Diagrams and Flow Graphs
2.9 State Variables
2.10 Other State-Variable Formulations
2.11 Transfer Functions
2.12 Solutions of the State Equations
   Recursive Solution
   z-Transform Method
   Numerical Method via Digital Computer
   Properties of the State Transition Matrix
2.13 Linear Time-Varying Systems
2.14 Summary
References and Further Readings
Problems

Chapter 3: Sampling and Reconstruction
3.1 Introduction
3.2 Sampled-Data Control Systems
3.3 The Ideal Sampler
3.4 Evaluation of E*(s)
3.5 Results from the Fourier Transform
3.6 Properties of E*(s)
3.7 Data Reconstruction
   Zero-Order Hold
   First-Order Hold
   Fractional-Order Holds
3.8 Summary
References and Further Readings
Problems

Chapter 4: Open-Loop Discrete-Time Systems
4.1 Introduction
4.2 The Relationship Between E(z) and E*(s)
4.3 The Pulse Transfer Function
4.4 Open-Loop Systems Containing Digital Filters
4.5 The Modified z-Transform
4.6 Systems with Time Delays
4.7 Nonsynchronous Sampling
4.8 State-Variable Models
4.9 Review of Continuous-Time State Variables
4.10 Discrete-Time State Equations
# Table of Contents

4.11 Practical Calculations
4.12 Summary
References and Further Readings
Problems

Chapter 5: Closed-Loop Systems
   5.1 Introduction
   5.2 Preliminary Concepts
   5.3 Derivation Procedure
   5.4 State-Variable Models
   5.5 Summary
   References and Further Readings
   Problems

Chapter 6: System Time-Response Characteristics
   6.1 Introduction
   6.2 System Time Response
   6.3 System Characteristic Equation
   6.4 Mapping the s-Plane into the z-Plane
   6.5 Steady-State Accuracy
   6.6 Simulation
   6.7 Control Software
   6.8 Summary
   References and Further Readings
   Problems

Chapter 7: Stability Analysis Techniques
   7.1 Introduction
   7.2 Stability
   7.3 Bilinear Transformation
   7.4 The Routh-Hurwitz Criterion
   7.5 Jury's Stability Test
   7.6 Root Locus
   7.7 The Nyquist Criterion
   7.8 The Bode Diagram
   7.9 Interpretation of the Frequency Response
   7.10 Closed-Loop Frequency Response
   7.11 Summary
   References and Further Readings
   Problems
Table of Contents

Chapter 8: Digital Controller Design
  8.1 Introduction
  8.2 Control System Specifications
    Steady-State Accuracy
    Transient Response
    Relative Stability
    Sensitivity
    Disturbance Rejection
    Control Effort
  8.3 Compensation
  8.4 Phase-Lag Compensation
  8.5 Phase-Lead Compensation
  8.6 Phase-Lead Design Procedure
  8.7 Lag-Lead Compensation
  8.8 Integration and Differentiation Filters
  8.9 PID Controllers
  8.10 PID Controller Design
  8.11 Design by Root Locus
  8.12 Summary
  References and Further Readings
  Problems

Chapter 9: Pole-Assignment Design and State Estimation
  9.1 Introduction
  9.2 Pole Assignment
  9.3 State Estimation
    Observer Model
    Errors in Estimation
    Error Dynamics
    Controller Transfer Function
    Closed-Loop Characteristic Equation
    Closed-Loop State Equations
  9.4 Reduced-Order Observers
  9.5 Current Observers
  9.6 Controllability and Observability
  9.7 Systems with Inputs
  9.8 Summary
  References and Further Readings
  Problems

Chapter 10: System Identification of Discrete-Time Systems
Table of Contents

10.1 Introduction
10.2 Identification of Static Systems
10.3 Identification of Dynamic Systems
10.4 Black-Box Identification
10.5 Least-Squares System Identification
10.6 Estimating Transfer Functions with Partly Known Poles and Zeros
10.7 Recursive Least-Squares System Identification
10.8 Practical Factors for Identification
   Choice of Input
   Choice of Sampling Frequency
   Choice of Signal Scaling
10.9 Summary
References and Further Readings
Problems

Chapter 11: Linear Quadratic Optimal Control
11.1 Introduction
11.2 The Quadratic Cost Function
11.3 The Principle of Optimality
11.4 Linear Quadratic Optimal Control
11.5 The Minimum Principle
11.6 Steady-State Optimal Control
11.7 Optimal State Estimation Kalman Filters
11.8 Least-Squares Minimization
11.9 Summary
References and Further Readings
Problems

Chapter 12: Case Studies
12.1 Introduction
12.2 Servomotor System
   System Model
   Design
12.3 Environmental Chamber Control System
   Temperature Control System
12.4 Aircraft Landing System
   Plant Model
   Design
12.5 Neonatal Fractional Inspired Oxygen
   Plant Transfer Function
Table of Contents

Taubes PID Controller
MATLAB pidtool PIDF Controllers
12.6 Topology Identification in Electric Power System Models
References
Appendix
  Appendix I: Design Equations
  Appendix II: Masons Gain Formula
  References
  Appendix III: Evaluation of E*(s)
  References
  Appendix IV: Review of Matrices
    Algebra of Matrices
    Other Relationships
    References
  Appendix V: The Laplace Transform
    Introduction
    Properties of the Laplace Transform
    Differential Equations and Transfer Functions
    References
    Problems
  Appendix VI: z-Transform Tables
Index