### **Contents**

# PART ONE INTRODUCTION TO PROCESS CONTROL

-	<b>T</b> .			•	~	-
١.	Intro	duction	to l	'rocess	Control	

1.1	Representative Process Control Problems	1
1 2	Tilliand and the Electrical A. Dilliand and D. Company	_

- 1.2 Illustrative Example—A Blending Process 3
- 1.3 Classification of Process Control Strategies 5
- 1.4 A More Complicated Example— A Distillation Column 7
- 1.5 The Hierarchy of Process Control Activities 8
- 1.6 An Overview of Control System Design 10

#### 2. Theoretical Models of Chemical Processes 15

- 2.1 The Rationale for Dynamic Process Models 15
- 2.2 General Modeling Principles 17
- 2.3 Degrees of Freedom Analysis 21
- 2.4 Dynamic Models of Representative Processes 22
- 2.5 Process Dynamics and Mathematical Models 35

#### PART TWO DYNAMIC BEHAVIOR OF PROCESSES

#### 3. Transfer Function Models 43

- 3.1 An Illustrative Example: A Continuous Blending System 43
- 3.2 Transfer Functions of Complicated Models 45
- 3.3 Properties of Transfer Functions 46
- 3.4 Linearization of Nonlinear Models 49

#### 4. Dynamic Behavior of First-Order and Second-Order Processes 58

- 4.1 Standard Process Inputs 58
- 4.2 Response of First-Order Processes 61

- 4.3 Response of Integrating Processes 64
- 4.4 Response of Second-Order Processes 66

#### 5. Dynamic Response Characteristics of More Complicated Processes 78

- 5.1 Poles and Zeros and Their Effect on Process Response 78
- 5.2 Processes with Time Delays 82
- 5.3 Approximation of Higher-Order Transfer Functions 86
- 5.4 Interacting and Noninteracting Processes 88
- 5.5 State-Space and Transfer Function Matrix Models 90
- 5.6 Multiple-Input, Multiple-Output (MIMO) Processes 93

## 6. Development of Empirical Models from Process Data 102

- 6.1 Model Development Using Linear or Nonlinear Regression 103
- 6.2 Fitting First- and Second-Order Models Using Step Tests 107
- 6.3 Neural Network Models 112
- 6.4 Development of Discrete-Time Dynamic Models 113
- 6.5 Identifying Discrete-Time Models from Experimental Data 115

#### PART THREE FEEDBACK AND FEEDFORWARD CONTROL

#### 7. Feedback Controllers 124

- 7.1 Introduction 124
- 7.2 Basic Control Modes 126
- 7.3 Features of PID Controllers 131
- 7.4 On-Off Controllers 134
- 7.5 Typical Responses of Feedback Control Systems 134
- 7.6 Digital Versions of PID Controllers 135

8. Control System Instrumentation 141

8.2 Final Control Elements 147

8.3 Signal Transmission and Digital Communication 153

8.4 Accuracy in Instrumentation 154

8.1 Sensors, Transmitters, and Transducers 142

9. Process Safety and Process Control 160	14. Feedforward and Ratio Control 271
<ul> <li>9.1 Layers of Protection 161</li> <li>9.2 Alarm Management 165</li> <li>9.3 Abnormal Event Detection 169</li> <li>9.4 Risk Assessment 171</li> </ul>	<ul> <li>14.1 Introduction to Feedforward Control 271</li> <li>14.2 Ratio Control 273</li> <li>14.3 Feedforward Controller Design Based on Steady-State Models 275</li> </ul>
<ul> <li>10. Dynamic Behavior and Stability of Closed-Loop Control Systems 176</li> <li>10.1 Block Diagram Representation 176</li> <li>10.2 Closed-Loop Transfer Functions 179</li> <li>10.3 Closed-Loop Responses of Simple Control Systems 182</li> <li>10.4 Stability of Closed-Loop Control Systems 188</li> <li>10.5 Root Locus Diagrams 194</li> </ul>	<ul> <li>14.4 Feedforward Controller Design Based on Dynamic Models 277</li> <li>14.5 The Relationship Between the Steady-State and Dynamic Design Methods 281</li> <li>14.6 Configurations for Feedforward-Feedback Control 282</li> <li>14.7 Tuning Feedforward Controllers 282</li> <li>PART FOUR</li> <li>ADVANCED PROCESS CONTROL</li> </ul>
11. PID Controller Design, Tuning, and Troubleshooting 204	15. Enhanced Single-Loop Control Strategies 288
<ul> <li>11.1 Performance Criteria for Closed-Loop Systems 204</li> <li>11.2 Model-Based Design Methods 206</li> <li>11.3 Controller Tuning Relations 211</li> <li>11.4 Controllers with Two Degrees of Freedom 216</li> <li>11.5 On-Line Controller Tuning 217</li> <li>11.6 Guidelines for Common Control Loops 223</li> <li>11.7 Troubleshooting Control Loops 225</li> </ul>	<ul> <li>15.1 Cascade Control 288</li> <li>15.2 Time-Delay Compensation 293</li> <li>15.3 Inferential Control 296</li> <li>15.4 Selective Control/Override Systems 297</li> <li>15.5 Nonlinear Control Systems 300</li> <li>15.6 Adaptive Control Systems 307</li> <li>16. Multiloop and Multivariable Control 317</li> <li>16.1 Process Interactions and Control Loop</li> </ul>
12. Control Strategies at the Process Unit Level 232	Interactions 317
<ul> <li>12.1 Degrees of Freedom Analysis for Process Control 232</li> <li>12.2 Selection of Controlled, Manipulated, and Measured Variables 234</li> <li>12.3 Applications 238</li> <li>13. Frequency Response Analysis and Control System Design 248</li> </ul>	<ul> <li>16.2 Pairing of Controlled and Manipulated Variables 323</li> <li>16.3 Singular Value Analysis 330</li> <li>16.4 Tuning of Multiloop PID Control Systems 334</li> <li>16.5 Decoupling and Multivariable Control Strategies 334</li> <li>16.6 Strategies for Reducing Control Loop Interactions 336</li> </ul>
13.1 Sinusoidal Forcing of a First-Order Process 248	17. Digital Sampling, Filtering, and Control 344
13.2 Sinusoidal Forcing of an <i>n</i> th-Order Process 249	<ul><li>17.1 Sampling and Signal Reconstruction 344</li><li>17.2 Signal Processing and Data Filtering 347</li></ul>

13.3 Bode Diagrams 251

13.4 Frequency Response Characteristics of

Feedback Controllers 255

13.5 Nyquist Diagrams 260 13.6 Bode Stability Criterion 260

13.7 Gain and Phase Margins 264

<ul> <li>18.2 Sequential and Logic Control 374</li> <li>18.3 Control During the Batch 380</li> <li>18.4 Run-to-Run Control 386</li> <li>18.5 Batch Production Management 387</li> </ul>	23. Dynamics and Control of Biological Systems 470 24.1 Systems Biology 470 24.2 Gene Regulatory Control 472			
Chapters 19 through 23 are online at www.wiley.com/go/global/seborg	24.2 Gene Regulatory Control 472 24.3 Signal Transduction Networks 476  Appendix A: Laplace Transforms A-1			
19. Real-Time Optimization 395	A.1 The Laplace Transform of Representative			
<ul> <li>19.1 Basic Requirements in Real-Time Optimization 396</li> <li>19.2 The Formulation and Solution of RTO Problems 399</li> <li>19.3 Unconstrained and Constrained</li> </ul>	Functions A-1 A.2 Solution of Differential Equations by Laplace Transform Techniques A-5 A.3 Partial Fraction Expansion A-7 A.4 Other Laplace Transform Properties A-10 A.5 A Transient Response Example A-13			
Optimization 401 19.4 Linear Programming 404 19.5 Quadratic and Nonlinear Programming 408	Appendix B: Digital Process Control Systems: Hardware and Software A-21			
20. Model Predictive Control 414	<ul> <li>B.1 Distributed Digital Control Systems A-22</li> <li>B.2 Analog and Digital Signals and Data</li> <li>Transfer A-22</li> </ul>			
<ul> <li>20.1 Overview of Model Predictive Control 414</li> <li>20.2 Predictions for SISO Models 416</li> <li>20.3 Predictions for MIMO Models 421</li> <li>20.4 Model Predictive Control</li> </ul>	<ul> <li>B.3 Microprocessors and Digital Hardware in Process Control A-24</li> <li>B.4 Software Organization A-27</li> </ul>			
Calculations 423 20.5 Set-Point Calculations 427	Appendix C: Review of Thermodynamic Concepts for Conservation Equations A-34			
<ul><li>20.6 Selection of Design and Tuning</li><li>Parameters 429</li><li>20.7 Implementation of MPC 434</li></ul>	C.1 Single-Component Systems A-34 C.2 Multicomponent Systems A-35			
21. Process Monitoring 439	Appendix D: Control Simulation Software A-36			
<ul> <li>21.1 Traditional Monitoring     Techniques 440</li> <li>21.2 Quality Control Charts 441</li> <li>21.3 Extensions of Statistical Process     Control 447</li> </ul>	<ul> <li>D.1 MATLAB Operations and Equation Solving A-36</li> <li>D.2 Computer Simulation with Simulink A-38</li> <li>D.3 Computer Simulation with LabVIEW A-40</li> </ul>			
21.4 Multivariate Statistical Techniques 449 21.5 Control Performance Monitoring 451	Appendix E: Process Control Modules A-43  E.1. Introduction A-43  E.2. Module Organization A-43			

PART FIVE

**SYSTEMS** 

APPLICATIONS TO BIOLOGICAL

22.1 Process Modeling and Control in Pharmaceutical Operations 456

22.2 Process Modeling and Control for Drug

22. Biosystems Control Design 456

Delivery 462

17.3 z-Transform Analysis for Digital

17.6 Minimum Variance Control 364

17.4 Tuning of Digital PID Controllers 358

17.5 Direct Synthesis for Design of Digital

Control 352

Controllers 360

18. Batch Process Control 371

18.1 Batch Control Systems 373

E.3.	Hardware an	d Software Requirements	A-44	Appendix H:	Dynamic Models and
E.4.	Installation	A-44			<b>Parameters Used for</b>

E.5. Running the Software A-44

Appendices F through K are online at www.wiley.com/go/global/seborg

#### Appendix F: Introduction to Plantwide Control A-45

- F.1 Plantwide Control Issues A-45
- F.2 Hypothetical Plant for Plantwide Control Studies A-47
- F.3 Internal Feedback of Material and Energy A-51
- F.4 Interaction of Plant Design and Control System Design A-59

#### Appendix G: Plantwide Control System Design A-63

- G.1 Procedures for the Design of Plantwide Control Systems A-63
- G.2 A Systematic Procedure for Plantwide Control System Design A-64
- G.3 Case Study: The Reactor/Flash Unit Plant A-67
- G.4 Effect of Control Structure on Closed-Loop Performance A-78

# Parameters Used for Plantwide Control Chapters A-82

- H.1 Energy Balance and Parameters for the Reactor/Distillation Column Model A-82
- H.2 Core Reactor/Flash Unit Model and Parameters A-82

#### Appendix I: Instrumentation Symbols A-88

#### Appendix J: Review of Basic Concepts from Probability and Statistics A-90

- J.1 Probability Concepts A-90
- J.2 Means and Variances A-91
- J.3 Standard Normal Distribution A-91
- J.4 Error Analysis A-92

## Appendix K: Contour Mapping and the Principle of the Argument A-93

K.1 Development of the Nyquist Stability Criterion A-93

#### Index I-1