Understanding Process Dynamics and Control

Understanding Process Dynamics and Control presents a fresh look at process control, with a state-space approach presented in parallel with the traditional approach to explain the strategies used in industry today.

Modern time-domain and traditional transform-domain methods are integrated throughout and the advantages and limitations of each approach are explained; the fundamental theoretical concepts and methods of process control are applied to practical problems.

To ensure understanding of the mathematical calculations involved, MATLAB is included for numeric calculations and Maple for symbolic calculations, with the math behind every method carefully explained so that students develop a clear understanding of how and why the software tools work.

Written for a one-semester course with optional advanced-level material, features include solved examples, cases including a variety of chemical process examples, chapter summaries, key terms and concepts, as well as over 240 end-of-chapter problems, including focused computational exercises.

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Understanding Process Dynamics and Control

Costas Kravaris
Texas A & M University

Ioannis K. Kookos
University of Patras, Greece
Dedicated to our families,

Irene, Michael, Evangeline and Cosmas

C. Kravaris

and

Natasa, Kostas and Georgia

I.K. Kookos
# Contents

Preface ........................................... page xvii

1 INTRODUCTION ........................................ 1
   Study Objectives ........................................ 1
   1.1 What is Process Control? ........................... 1
   1.2 Feedback Control System: Key Ideas, Concepts and Terminology .......... 2
   1.3 Process Control Notation and Control Loop Representation .......... 8
   1.4 Understanding Process Dynamics is a Prerequisite for Learning Process Control .......... 9
   1.5 Some Historical Notes .................................. 11
   Learning Summary ........................................ 15
   Terms and Concepts ....................................... 15
   Further Reading ........................................... 16
   Problems ............................................... 17

2 DYNAMIC MODELS FOR CHEMICAL PROCESS SYSTEMS ........... 18
   Study Objectives ........................................ 18
   2.1 Introduction ........................................... 18
   2.2 Conservation Laws ..................................... 20
   2.3 Modeling Examples of Nonreacting Systems .................... 23
   2.4 Modeling of Reacting Systems ......................... 28
   2.5 Modeling of Equilibrium Separation Systems ................. 37
   2.6 Modeling of Simple Electrical and Mechanical Systems .......... 39
   2.7 Software Tools ........................................ 43
   Learning Summary ........................................ 45
   Terms and Concepts ....................................... 46
   Further Reading ........................................... 46
   Problems ............................................... 47

3 FIRST-ORDER SYSTEMS .................................. 55
   Study Objectives ........................................ 55
   3.1 Examples of First-Order Systems .......................... 55
   3.2 Deviation Variables .................................... 58
   3.3 Solution of Linear First-Order Differential Equations with Constant Coefficients .......... 59
3.4 The Choice of Reference Steady State Affects the Mathematical Form of the Dynamics Problem 62
3.5 Unforced Response: Effect of Initial Condition under Zero Input 63
3.6 Forced Response: Effect of Nonzero Input under Zero Initial Condition 63
3.7 Standard Idealized Input Variations 65
3.8 Response of a First-Order System to a Step Input 68
3.9 Response of a First-Order System to a Pulse Input 73
3.10 Response of a First-Order System to a Ramp Input 75
3.11 Response of a First-Order System to a Sinusoidal Input 77
3.12 Response of a First-Order System to an Arbitrary Input – Time Discretization of the First-Order System 82
3.13 Another Example of a First-Order System: Liquid Storage Tank 88
3.14 Nonlinear First-Order Systems and their Linearization 94
3.15 Liquid Storage Tank with Input Bypass 97
3.16 General Form of a First-Order System 99
3.17 Software Tools 102
Learning Summary 106
Terms and Concepts 107
Further Reading 108
Problems 108

4 CONNECTIONS OF FIRST-ORDER SYSTEMS 115
Study Objectives 115
4.1 First-Order Systems Connected in Series 115
4.2 First-Order Systems Connected in Parallel 119
4.3 Interacting First-Order Systems 122
4.4 Response of First-Order Systems Connected in Series or in Parallel 123
4.5 Software Tools 132
Learning Summary 134
Terms and Concepts 136
Further Reading 136
Problems 137

5 SECOND-ORDER SYSTEMS 144
Study Objectives 144
5.1 A Classical Example of a Second-Order System 145
5.2 A Second-Order System can be Described by Either a Set of Two First-Order ODEs or a Single Second-Order ODE 147
5.3 Calculating the Response of a Second-Order System – Step Response of a Second-Order System 148
5.4 Qualitative and Quantitative Characteristics of the Step Response of a Second-Order System 154
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>Frequency Response and Bode Diagrams of Second-Order Systems</td>
<td>159</td>
</tr>
<tr>
<td>5.6</td>
<td>The General Form of a Linear Second-Order System</td>
<td>161</td>
</tr>
<tr>
<td>5.7</td>
<td>Software Tools</td>
<td>163</td>
</tr>
<tr>
<td></td>
<td>Learning Summary</td>
<td>166</td>
</tr>
<tr>
<td></td>
<td>Terms and Concepts</td>
<td>166</td>
</tr>
<tr>
<td></td>
<td>Further Reading</td>
<td>167</td>
</tr>
<tr>
<td></td>
<td>Problems</td>
<td>168</td>
</tr>
<tr>
<td>6</td>
<td>LINEAR HIGHER-ORDER SYSTEMS</td>
<td>171</td>
</tr>
<tr>
<td>6.1</td>
<td>Representative Examples of Higher-Order Systems – Using Vectors and Matrices to Describe a Linear System</td>
<td>171</td>
</tr>
<tr>
<td>6.2</td>
<td>Steady State of a Linear System – Deviation Variables</td>
<td>175</td>
</tr>
<tr>
<td>6.3</td>
<td>Using the Laplace-Transform Method to Solve the Linear Vector Differential Equation and Calculate the Response – Transfer Function of a Linear System</td>
<td>177</td>
</tr>
<tr>
<td>6.4</td>
<td>The Matrix Exponential Function</td>
<td>179</td>
</tr>
<tr>
<td>6.5</td>
<td>Solution of the Linear Vector Differential Equation using the Matrix Exponential Function</td>
<td>182</td>
</tr>
<tr>
<td>6.6</td>
<td>Dynamic Response of a Linear System</td>
<td>187</td>
</tr>
<tr>
<td>6.7</td>
<td>Response to an Arbitrary Input – Time Discretization of a Linear System</td>
<td>191</td>
</tr>
<tr>
<td>6.8</td>
<td>Calculating the Response of a Second-Order System via the Matrix Exponential Function</td>
<td>195</td>
</tr>
<tr>
<td>6.9</td>
<td>Multi-Input–Multi-Output Linear Systems</td>
<td>197</td>
</tr>
<tr>
<td>6.10</td>
<td>Software Tools</td>
<td>202</td>
</tr>
<tr>
<td></td>
<td>Learning Summary</td>
<td>206</td>
</tr>
<tr>
<td></td>
<td>Terms and Concepts</td>
<td>206</td>
</tr>
<tr>
<td></td>
<td>Further Reading</td>
<td>206</td>
</tr>
<tr>
<td></td>
<td>Problems</td>
<td>207</td>
</tr>
<tr>
<td>7</td>
<td>EIGENVALUE ANALYSIS – ASYMPTOTIC STABILITY</td>
<td>215</td>
</tr>
<tr>
<td>7.1</td>
<td>Introduction</td>
<td>215</td>
</tr>
<tr>
<td>7.2</td>
<td>The Role of System Eigenvalues on the Characteristics of the Response of a Linear System</td>
<td>216</td>
</tr>
<tr>
<td>7.3</td>
<td>Asymptotic Stability of Linear Systems</td>
<td>220</td>
</tr>
<tr>
<td>7.4</td>
<td>Properties of the Forced Response of Asymptotically Stable Linear Systems</td>
<td>224</td>
</tr>
<tr>
<td>7.5</td>
<td>The Role of Eigenvalues in Time Discretization of Linear Systems – Stability Test on a Discretized Linear System</td>
<td>225</td>
</tr>
<tr>
<td>7.6</td>
<td>Nonlinear Systems and their Linearization</td>
<td>228</td>
</tr>
<tr>
<td>7.7</td>
<td>Software Tools</td>
<td>240</td>
</tr>
</tbody>
</table>
Contents

Learning Summary 244
Terms and Concepts 245
Further Reading 245
Problems 245

8 TRANSFER-FUNCTION ANALYSIS OF THE INPUT–OUTPUT BEHAVIOR 251
Study Objectives 251
8.1 Introduction 251
8.2 A Transfer Function is a Higher-Order Differential Equation in Disguise 252
8.3 Proper and Improper Transfer Functions – Relative Order 257
8.4 Poles, Zeros and Static Gain of a Transfer Function 259
8.5 Calculating the Output Response to Common Inputs from the Transfer Function – the Role of Poles in the Response 261
8.6 Effect of Zeros on the Step Response 268
8.7 Bounded-Input–Bounded-Output (BIBO) Stability 273
8.8 Asymptotic Response of BIBO-Stable Linear Systems 275
8.9 Software Tools 279
Learning Summary 287
Terms and Concepts 287
Further Reading 288
Problems 288

9 FREQUENCY RESPONSE 297
Study Objectives 297
9.1 Introduction 297
9.2 Frequency Response and Bode Diagrams 298
9.3 Straight-Line Approximation Method for Sketching Bode Diagrams 303
9.4 Low-Frequency and High-Frequency Response 311
9.5 Nyquist Plots 312
9.6 Software Tools 319
Learning Summary 321
Terms and Concepts 321
Further Reading 322
Problems 322

10 THE FEEDBACK CONTROL SYSTEM 327
Study Objectives 327
10.1 Heating Tank Process Example 327
10.2 Common Sensors and Final Control Elements 329
10.3 Block-Diagram Representation of the Heating Tank Process Example 332
13.3 Time Discretization of the Closed-Loop System 422
13.4 State-Space Description of Nonlinear Closed-Loop Systems 426
13.5 Software Tools 428
Learning Summary 434
Further Reading 435
Problems 435

14 SYSTEMS WITH DEAD TIME 437
Study Objectives 437
14.1 Introduction 437
14.2 Approximation of Dead Time by Rational Transfer Functions 446
14.3 Parameter Estimation for FOPDT Systems 456
14.4 Feedback Control of Systems with Dead Time – Closed-Loop Stability Analysis 460
14.5 Calculation of Closed-Loop Response for Systems involving Dead Time 467
14.6 Software Tools 473
Learning Summary 475
Terms and Concepts 476
Further Reading 476
Problems 476

15 PARAMETRIC ANALYSIS OF CLOSED-LOOP DYNAMICS – ROOT-LOCUS DIAGRAMS 484
Study Objectives 484
15.1 What is a Root-Locus Diagram? Some Examples 484
15.2 Basic Properties of the Root Locus – Basic Rules for Sketching Root-Locus Diagrams 502
15.3 Further Properties of the Root Locus – Additional Rules for Sketching Root-Locus Diagrams 508
15.4 Calculation of the Points of Intersection of the Root Locus with the Imaginary Axis 524
15.5 Root Locus with Respect to Other Controller Parameters 527
15.6 Software Tools 531
Learning Summary 536
Terms and Concepts 537
Further Reading 537
Problems 537

16 OPTIMAL SELECTION OF CONTROLLER PARAMETERS 541
Study Objectives 541
16.1 Control Performance Criteria 541
16.2 Analytic Calculation of Quadratic Criteria for a Stable System and a Step Input 549
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.3</td>
<td>Calculation of Optimal Controller Parameters for Quadratic Criteria</td>
<td>557</td>
</tr>
<tr>
<td>16.4</td>
<td>Software Tools</td>
<td>563</td>
</tr>
<tr>
<td></td>
<td>Learning Summary</td>
<td>570</td>
</tr>
<tr>
<td></td>
<td>Terms and Concepts</td>
<td>571</td>
</tr>
<tr>
<td></td>
<td>Further Reading</td>
<td>571</td>
</tr>
<tr>
<td></td>
<td>Problems</td>
<td>572</td>
</tr>
<tr>
<td>17</td>
<td>BODE AND NYQUIST STABILITY CRITERIA – GAIN AND PHASE MARGINS</td>
<td>575</td>
</tr>
<tr>
<td></td>
<td>Study Objectives</td>
<td>575</td>
</tr>
<tr>
<td>17.1</td>
<td>Introduction</td>
<td>575</td>
</tr>
<tr>
<td>17.2</td>
<td>The Bode Stability Criterion</td>
<td>576</td>
</tr>
<tr>
<td>17.3</td>
<td>The Nyquist Stability Criterion</td>
<td>594</td>
</tr>
<tr>
<td>17.4</td>
<td>Example Applications of the Nyquist Criterion</td>
<td>597</td>
</tr>
<tr>
<td>17.5</td>
<td>Software Tools</td>
<td>604</td>
</tr>
<tr>
<td></td>
<td>Learning Summary</td>
<td>607</td>
</tr>
<tr>
<td></td>
<td>Terms and Concepts</td>
<td>607</td>
</tr>
<tr>
<td></td>
<td>Further Reading</td>
<td>608</td>
</tr>
<tr>
<td></td>
<td>Problems</td>
<td>608</td>
</tr>
<tr>
<td>18</td>
<td>MULTI-INPUT–MULTI-OUTPUT SYSTEMS</td>
<td>613</td>
</tr>
<tr>
<td></td>
<td>Study Objectives</td>
<td>613</td>
</tr>
<tr>
<td>18.1</td>
<td>Introduction</td>
<td>613</td>
</tr>
<tr>
<td>18.2</td>
<td>Dynamic Response of MIMO Linear Systems</td>
<td>620</td>
</tr>
<tr>
<td>18.3</td>
<td>Feedback Control of MIMO Systems: State-Space versus Transfer-Function Description of the Closed-Loop System</td>
<td>623</td>
</tr>
<tr>
<td>18.4</td>
<td>Interaction in MIMO Systems</td>
<td>627</td>
</tr>
<tr>
<td>18.5</td>
<td>Decoupling in MIMO Systems</td>
<td>632</td>
</tr>
<tr>
<td>18.6</td>
<td>Software Tools</td>
<td>634</td>
</tr>
<tr>
<td></td>
<td>Learning Summary</td>
<td>638</td>
</tr>
<tr>
<td></td>
<td>Terms and Concepts</td>
<td>639</td>
</tr>
<tr>
<td></td>
<td>Further Reading</td>
<td>639</td>
</tr>
<tr>
<td></td>
<td>Problems</td>
<td>639</td>
</tr>
<tr>
<td>19</td>
<td>SYNTHESIS OF MODEL-BASED FEEDBACK CONTROLLERS</td>
<td>641</td>
</tr>
<tr>
<td></td>
<td>Study Objectives</td>
<td>641</td>
</tr>
<tr>
<td>19.1</td>
<td>Introduction</td>
<td>641</td>
</tr>
<tr>
<td>19.2</td>
<td>Nearly Optimal Model-Based Controller Synthesis</td>
<td>648</td>
</tr>
<tr>
<td>19.3</td>
<td>Controller Synthesis for Low-Order Models</td>
<td>650</td>
</tr>
<tr>
<td>19.4</td>
<td>The Smith Predictor for Processes with Large Dead Time</td>
<td>657</td>
</tr>
<tr>
<td>19.5</td>
<td>Effect of Modeling Error</td>
<td>660</td>
</tr>
<tr>
<td>19.6</td>
<td>State-Space Form of the Model-Based Controller</td>
<td>668</td>
</tr>
</tbody>
</table>
## Contents

19.7 Model-Based Controller Synthesis for MIMO Systems  674  
Learning Summary  678  
Terms and Concepts  678  
Further Reading  679  
Problems  679  

### 20 CASCADE, RATIO AND FEEDFORWARD CONTROL  683  
Study Objectives  683  
20.1 Introduction  683  
20.2 Cascade Control  684  
20.3 Ratio Control  694  
20.4 Feedforward Control  695  
20.5. Model-Based Feedforward Control  700  
Learning Summary  714  
Terms and Concepts  715  
Further Reading  715  
Problems  716  

### APPENDIX A LAPLACE TRANSFORM  719  
A.1 Definition of the Laplace Transform  719  
A.2 Laplace Transforms of Elementary Functions  720  
A.3 Properties of Laplace Transforms  721  
A.4 Inverse Laplace Transform  725  
A.5 Calculation of the Inverse Laplace Transform of Rational Functions via Partial Fraction Expansion  725  
A.6 Solution of Linear Ordinary Differential Equations using the Laplace Transform  732  
A.7 Software Tools  735  
Problems  739  

### APPENDIX B BASIC MATRIX THEORY  743  
B.1 Basic Notations and Definitions  743  
B.2 Determinant of a Square Matrix  747  
B.3 Matrix Inversion  749  
B.4 Eigenvalues  750  
B.5 The Cayley–Hamilton Theorem and the Resolvent Identity  752  
B.6 Differentiation and Integration of Matrices  755  
B.7 Software Tools  756  

Index  760
Preface

Scope of the Book

When we took undergraduate process dynamics and control in the 1970s and the 1980s, the entire course was built around the Laplace transform and the transfer function. This conceptual and methodological approach has been in place in undergraduate chemical engineering education since the 1960s and even the 1950s, and it reflected the development and widespread use of electronic PID control systems, for which it provided a very adequate background for the chemical engineering graduates. Today, the vast majority of undergraduate chemical process dynamics and control courses still follow exactly the same conceptual approach, revolving around the Laplace transform and the transfer function. But control technology has changed a lot during the past 60 years. Even though PID controllers are still used, model-predictive control has evolved into an industrial standard for advanced applications. But model-predictive control is formulated in state space and in discrete time, whereas the standard control course is in the transform domain and in continuous time. There is a big conceptual gap between what is taught in the classroom and the industrial state of the art. This gap is well recognized within the chemical process control community, as is the need to bridge this gap. It is aim of this book to propose a realistic solution on how to bridge this gap, so that chemical engineering graduates are better prepared in using modern control technology. This book has evolved after many years of teaching experimentation at Texas A&M University and the University of Patras.

The main feature of this book is the introduction of state-space methods at the undergraduate level, not at the end of the book, but from day one. There are two main reasons that this is feasible. The first is that state-space concepts and methods are easy to grasp and comprehend, since they are in the time domain. The second is the availability of powerful computational tools that emerge from the state-space methods and can be implemented through user-friendly software packages. Once the student is given the key ideas and concepts in the time domain, he/she can painlessly apply them computationally.

Of course, one should not downplay the significance of manual calculations in developing an understanding of dynamic behavior in open loop and in closed loop. To this end, Laplace-transform methods offer a distinct advantage over time-domain methods. Even though industrial practitioners keep telling us that “there is no Laplace domain in their plant,” there is no question about its educational value. The concept of the transfer function is also an
Preface

invaluable educational tool for the student to understand connections of dynamic systems, including the feedback loop, and also to calculate and appreciate frequency response characteristics. For this reason, Laplace-domain methods are used in this book, and they are used in parallel with state-space methods. Whenever a quick manual calculation is feasible, the student should be able to go to the “Laplace planet” and come back, whenever calculations are very involved or simulation is needed, the student should be able to handle it computationally using software.

This book offers a strong state-space component, both conceptually and computationally, and this is blended with the traditional analytical framework, in order to maximize the students’ understanding. But there is also an additional advantage. Because of its state-space component, this book brings the process dynamics and control course closer to other chemical engineering courses, such as the chemical reactor course. A chemical reactor course introduces local asymptotic stability in a state-space setting and tests it through eigenvalues, whereas a traditional control course defines stability in an input–output sense and tests it through the poles of the transfer function. This gap is nonexistent in the present book: asymptotic stability is defined and explained in a state-space context, input–output stability is defined and explained in a transfer function or convolution integral context, and the relationship of the two notions of stability is discussed. Moreover, there are a number of chemical reactor examples throughout the book that link the two courses in a synergistic manner.

A final comment should be made about the word “understanding” in the title of this book. It is our firm belief that engineers must have a thorough understanding of how their tools work, when do they work and why they work. If they treat a software package as a magic black box, without understanding what’s inside the box, they have not learned anything. For this reason, special care is taken in this book to explain the math that is behind every method presented, so that the student develops a clear understanding of how, when and why.

Organization of the Book

A general introduction is given in Chapter 1. A review of unsteady state material and energy balances is given in Chapter 2. Reviews of the Laplace transform and of basic matrix algebra are separate from the chapters, and are given in Appendices A and B.

Chapters 3–9 and the first half of Chapter 14 cover process dynamics. The approach taken is to start from the simplest dynamic systems (first-order systems) in Chapter 3, and then progressively generalize. Both time domain (including discrete time) and transfer function (including frequency response) start from Chapter 3 and are pursued in parallel in the subsequent chapters. Chapters 4 and 5 are generalizations, studying connections of first-order systems and inherently second-order systems. Chapters 6–9 cover the dynamic analysis of higher-order systems in both state space (Chapters 6 and 7) and transform domain (Chapters 8 and 9), including asymptotic stability and input–output stability. Dead time is postponed to Chapter 14. All the dynamics chapters are to be covered; the only part that is optional is
the second part of Chapter 9 on Nyquist diagrams, which is only needed in the second part of Chapter 17.

The rest of the chapters are on process control. Chapters 10–14 cover the basic feedback control concepts and analysis methods. Chapter 10 gives a general introduction to feedback control, and also defines the PID controller in both state-space and transfer function form. Chapters 11 and 12 do transfer function analysis of the feedback control loop, whereas in Chapter 13 the same analysis is done in state space. Chapter 14 discusses systems with deadtime, both open loop dynamics and feedback control. Deadtime is treated separately because of its distinct mathematical characteristics. Chapters 10–14 provide an absolute minimum for the feedback control part of the course. From that point, the instructor can choose what design methods he/she wants to put emphasis on, root locus (Chapter 15), optimization (Chapter 16), gain and phase margins (Chapter 17) or model-based (Chapter 19). Also, the instructor has the choice to discuss issues in multivariable control (Chapter 18) or stay SISO throughout the course. The last chapter (Chapter 20) discusses cascade, ratio and feedforward control. These control structures are discussed first at a conceptual level, and then model-based design for cascade and feedforward control is derived. The conceptual part is, in a sense, a continuation of Chapter 10 and it is essential to be taught; the model-based part is a continuation of Chapter 19.

The last section of each chapter is about software tools. The use of software for the application of the theory of the chapter is explained through simple examples. Two alternative software packages are used: MATLAB and its control systems toolbox is chosen because of its strength in numerical calculations, and Maple and its libraries (LinearAlgebra, inttrans, etc.) because of its strength in symbolic calculations.

The following table gives a sample syllabus for the process dynamics and control course at Texas A&M University, as it has been taught in the past three semesters. It reflects the personal choices of the instructor on (i) the design methods for the control part of the course (optimization and model-based are emphasized) and (ii) the pace of covering the material (slower at the beginning, faster at the end). Of course, there are many other options, depending on instructor priorities and students’ background.

<table>
<thead>
<tr>
<th>Topic</th>
<th>From the book</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>Chapter 1</td>
<td>1</td>
</tr>
<tr>
<td>Review of unsteady-state material</td>
<td>Chapter 2</td>
<td>1</td>
</tr>
<tr>
<td>and energy balances</td>
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<td>Review of the Laplace transform</td>
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<td>First-order systems</td>
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<td>Second-order systems</td>
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<td>Eigenvalue analysis, asymptotic</td>
<td>Chapter 7 and Appendix B (second half)</td>
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<td>stability</td>
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<td>Transfer-function analysis</td>
<td>Chapter 9 – Bode part</td>
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<td>Bode diagrams</td>
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## Preface

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<th>Topic</th>
<th>From the book</th>
<th>Hours</th>
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<tr>
<td>The feedback control system</td>
<td>Chapter 10</td>
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<td>Block-diagram simplification, closed-loop responses</td>
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<td>Systems with dead time</td>
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<td>Model-based control</td>
<td>Chapter 19, excluding MIMO</td>
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<td>Cascade, ratio and feedforward control</td>
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Costas Kravaris and Ioannis K. Kookos, October 2020