## **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.

**Costas Kravaris** is Professor of Chemical Engineering at Texas A&M University, USA. He has over 35 years of teaching experience in process dynamics and control classes at both undergraduate and graduate level. He is an active researcher in nonlinear control, nonlinear state estimation and nonlinear model reduction, with applications to chemical processes.

**Ioannis K. Kookos** is Professor of Process Systems Engineering, in the Department Chemical Engineering at the University of Patras, Greece. He received his BSc in Chemical Engineering from the National Technical University of Athens, Greece and his MSc (1994) and PhD (2001) in Process Systems Engineering from Imperial College, London (Centre for PSE). He then worked as a lecturer at the University of Manchester, Department of Chemical Engineering.

# **Cambridge Series in Chemical Engineering**

#### **Series Editor**

Arvind Varma, Purdue University

#### **Editorial Board**

Juan de Pablo, University of Chicago Michael Doherty, University of California-Santa Barbara Ignacio Grossman, Carnegie Mellon University Jim Yang Lee, National University of Singapore Antonios Mikos, Rice University

#### **Books in the Series**

Baldea and Daoutidis, Dynamics and Nonlinear Control of Integrated Process Systems Chamberlin. Radioactive Aerosols Chau, Process Control: A First Course with Matlab Cussler, Diffusion: Mass Transfer in Fluid Systems, Third Edition Cussler and Moggridge, Chemical Product Design, Second Edition De Pablo and Schieber, Molecular Engineering Thermodynamics Deen, Introduction to Chemical Engineering Fluid Mechanics Denn, Chemical Engineering: An Introduction Denn, Polymer Melt Processing: Foundations in Fluid Mechanics and Heat Transfer Dorfman and Daoutidis, Numerical Methods with Chemical Engineering Applications Duncan and Reimer, Chemical Engineering Design and Analysis: An Introduction, Second Edition Fan, Chemical Looping Partial Oxidation Gasification, Reforming, and Chemical Syntheses Fan and Zhu, Principles of Gas-Solid Flows Fox, Computational Models for Turbulent Reacting Flows Franses, Thermodynamics with Chemical Engineering Applications Leal, Advanced Transport Phenomena: Fluid Mechanics and Convective Transport Processes Lim and Shin, Fed-Batch Cultures: Principles and Applications of Semi-Batch Bioreactors Litster, Design and Processing of Particulate Products Marchisio and Fox, Computational Models for Polydisperse Particulate and Multiphase **Systems** 

Cambridge University Press 978-1-107-03558-4 — Understanding Process Dynamics and Control Costas Kravaris , Ioannis K. Kookos Frontmatter <u>More Information</u>

> Mewis and Wagner, Colloidal Suspension Rheology Morbidelli, Gavriilidis, and Varma, Catalyst Design: Optimal Distribution of Catalyst in Pellets, Reactors, and Membranes Nicoud, Chromatographic Processes Noble and Terry, Principles of Chemical Separations with Environmental Applications Orbey and Sandler, Modeling Vapor-Liquid Equilibria: Cubic Equations of State and their Mixing Rules Pfister, Nicoud, and Morbidelli, Continuous Biopharmaceutical Processes: Chromatography, Bioconjugation, and Protein Stability Petyluk, Distillation Theory and its Applications to Optimal Design of Separation Units Ramkrishna and Song, Cybernetic Modeling for Bioreaction Engineering Rao and Nott, An Introduction to Granular Flow Russell, Robinson, and Wagner, Mass and Heat Transfer: Analysis of Mass Contactors and Heat Exchangers Schobert, Chemistry of Fossil Fuels and Biofuels Shell, Thermodynamics and Statistical Mechanics Sirkar, Separation of Molecules, Macromolecules and Particles: Principles, Phenomena and Processes Slattery, Advanced Transport Phenomena Varma, Morbidelli, and Wu, Parametric Sensitivity in Chemical Systems Wolf, Bielser, and Morbidelli, Perfusion Cell Culture Processes for Biopharmaceuticals

# Understanding Process Dynamics and Control

#### **Costas Kravaris**

Texas A & M University

**Ioannis K. Kookos** University of Patras, Greece



Cambridge University Press 978-1-107-03558-4 — Understanding Process Dynamics and Control Costas Kravaris , Ioannis K. Kookos Frontmatter More Information

#### CAMBRIDGE UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314-321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi - 110025, India

79 Anson Road, #06-04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org Information on this title: www.cambridge.org/9781107035584 DOI: 10.1017/9781139565080

© Costas Kravaris and Ioannis K. Kookos 2021

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2021

Printed in the United Kingdom by TJ Books Limited, Padstow Cornwall

A catalogue record for this publication is available from the British Library.

ISBN 978-1-107-03558-4 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

## Dedicated to our families,

## Irene, Michael, Evangeline and Cosmas *C. Kravaris*

and

Natasa, Kostas and Georgia *I.K. Kookos* 

# Contents

Preface		<i>page</i> 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
		ix

#### x Contents

	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
	Lear	ning Summary	106
	Tern	ns and Concepts	107
	Furt	her Reading	108
	Prob	lems	108
4	CON	NECTIONS OF FIRST-ORDER SYSTEMS	115
	Stud	v 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
	Lear	ning Summary	134
	Tern	and Concepts	136
	Furt	her Reading	136
	Prob	lems	137
5	SECO	NND-ORDER SYSTEMS	144
-	Stud		144
	5 1	A Classical Example of a Second Order System	144
	5.1 5.2	A Classical Example of a Second-Order System A Second Order System can be Described by Either a Set of Two	145
	5.2	First Order ODEs or a Single Second Order ODE	147
	53	Calculating the Response of a Second Order System Stan Response of a	14/
	5.5	Second Order System	110
	5 /	Qualitative and Quantitative Characteristics of the Stan Despanse of a	140
	5.4	Second-Order System	154
		Scong-Order System	1.74

		Contents	xi
	5.5	Frequency Response and Bode Diagrams of Second-Order Systems	
		with $\zeta > 0$	159
	5.6	The General Form of a Linear Second-Order System	161
	5.7	Software Tools	163
	Lear	rning Summary	166
	Tern	ns and Concepts	166
	Furt	her Reading	167
	Prot	olems	168
6	LINE	AR HIGHER-ORDER SYSTEMS	171
	Stud	y Objectives	171
	6.1	Representative Examples of Higher-Order Systems – Using Vectors	
		and Matrices to Describe a Linear System	171
	6.2	Steady State of a Linear System – Deviation Variables	175
	6.3	Using the Laplace-Transform Method to Solve the Linear Vector	
		Differential Equation and Calculate the Response – Transfer Function	
		of a Linear System	177
	6.4	The Matrix Exponential Function	179
	6.5	Solution of the Linear Vector Differential Equation using the Matrix	
		Exponential Function	182
	6.6	Dynamic Response of a Linear System	187
	6.7	Response to an Arbitrary Input – Time Discretization of a Linear System	191
	6.8	Calculating the Response of a Second-Order System via the Matrix	
	6.0	Exponential Function	195
	6.9	Multi-Input–Multi-Output Linear Systems	197
	6.10	Software Tools	202
	Lear	ning Summary	206
	Tern	her Deadline	206
	Furt	ner Reading	206
	Prot	nems	207
7	EIGE	NVALUE ANALYSIS – ASYMPTOTIC STABILITY	215
	Stud	y Objectives	215
	7.1	Introduction	215
	7.2	The Role of System Eigenvalues on the Characteristics of the Response of	
		a Linear System	216
	7.3	Asymptotic Stability of Linear Systems	220
	7.4	Properties of the Forced Response of Asymptotically Stable Linear Systems	224
	7.5	The Role of Eigenvalues in Time Discretization of Linear Systems –	
		Stability Test on a Discretized Linear System	225
	7.6	Nonlinear Systems and their Linearization	228
	7.7	Software Tools	240

Cambridge University Press 978-1-107-03558-4 — Understanding Process Dynamics and Control Costas Kravaris , Ioannis K. Kookos Frontmatter <u>More Information</u>

#### xii 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

Contents	xiii
10.4 Further Examples of Process Control Loops	335
10.5 Commonly Used Control Laws	338
Learning Summary	345
Terms and Concepts	345
Further Reading	346
Problems	346
11 BLOCK-DIAGRAM REDUCTION AND TRANSIENT-RESPONSE CALCULATION	
IN A FEEDBACK CONTROL SYSTEM	350
Study Objectives	350
11.1 Calculation of the Overall Closed-Loop Transfer Functions in a	
Standard Feedback Control Loop	350
11.2 Calculation of Overall Transfer Functions in a Multi-Loop Feedback	
Control System	356
11.3 Stirred Tank Heater under Negligible Sensor Dynamics:	
Closed-Loop Response Calculation under P or PI Control	359
11.4 Software Tools	366
Learning Summary	372
Terms and Concepts	373
Further Reading	373
Problems	374
12 STEADY-STATE AND STABILITY ANALYSIS OF THE CLOSED-LOOP SYSTEM	377
Study Objectives	377
12.1 Steady-State Analysis of a Feedback Control System	377
12.2 Closed-Loop Stability, Characteristic Polynomial and	
Characteristic Equation	385
12.3 The Routh Criterion	389
12.4 Calculating Stability Limits via the Substitution $s = i\omega$	394
12.5 Some Remarks about the Role of Proportional,	
Integral and Derivative Actions	395
12.6 Software Tools	399
Learning Summary	404
Terms and Concepts	405
Further Reading	405
Problems	405
13 STATE-SPACE DESCRIPTION AND ANALYSIS OF THE CLOSED-LOOP SYSTEM	409
Study Objectives	409
13.1 State-Space Description and Analysis of the Heating Tank	409
13.2 State-Space Analysis of Closed-Loop Systems	415

#### xiv Contents

	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

	Contents	xv
16.3 Calculation of Ontimal Controller Parameters for Quadratic Cri	iteria	557
16.4 Software Tools	litila	563
Learning Summary		570
Terms and Concepts		571
Further Reading		571
Problems		572
17 BODE AND NYQUIST STABILITY CRITERIA – GAIN AND PHASE MARGINS		575
Study Objectives		575
17.1 Introduction		575
17.2 The Bode Stability Criterion		576
17.3 The Nyquist Stability Criterion		594
17.4 Example Applications of the Nyquist Criterion		597
17.5 Software Tools		604
Learning Summary		607
Terms and Concepts		607
Further Reading		608
Problems		608
18 MULTI-INPUT–MULTI-OUTPUT SYSTEMS		613
Study Objectives		613
18.1 Introduction		613
18.2 Dynamic Response of MIMO Linear Systems		620
18.3 Feedback Control of MIMO Systems: State-Space versus		
Transfer-Function Description of the Closed-Loop System		623
18.4 Interaction in MIMO Systems		627
18.5 Decoupling in MIMO Systems		632
18.6 Software Tools		634
Learning Summary		638
Terms and Concepts		639
Further Reading		639
Problems		639
19 SYNTHESIS OF MODEL-BASED FEEDBACK CONTROLLERS		641
Study Objectives		641
19.1 Introduction		641
19.2 Nearly Optimal Model-Based Controller Synthesis		648
19.3 Controller Synthesis for Low-Order Models		650
19.4 The Smith Predictor for Processes with Large Dead Time		657
19.5 Effect of Modeling Error		660
19.6 State-Space Form of the Model-Based Controller		668

#### xvi Contents

	19.7	Model-Based Controller Synthesis for MIMO Systems	674
	Lear	ning Summary	678
	Term	is and Concepts	678
	Furt	her Reading	679
	Prob	lems	679
20	CAS	CADE, RATIO AND FEEDFORWARD CONTROL	683
	Stud	y 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
	Lear	ning Summary	714
	Term	as and Concepts	715
	Furt	her Reading	715
	Prob	lems	715
APF	PEND	IX 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
	Prob	lems	739
APF	PEND	IX B BASIC MATRIX THEORY	743
	<b>B</b> .1	Basic Notations and Definitions	743
	<b>B</b> .2	Determinant of a Square Matrix	747
	<b>B</b> .3	Matrix Inversion	749
	B.4	Eigenvalues	750
	<b>B</b> .5	The Cayley–Hamilton Theorem and the Resolvent Identity	752
	<b>B</b> .6	Differentiation and Integration of Matrices	755
	<b>B</b> .7	Software Tools	756

760

Index

# 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, Laplacetransform 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

xvii

Cambridge University Press 978-1-107-03558-4 — Understanding Process Dynamics and Control Costas Kravaris , Ioannis K. Kookos Frontmatter <u>More Information</u>

#### xviii 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 statespace 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

Cambridge University Press 978-1-107-03558-4 — Understanding Process Dynamics and Control Costas Kravaris , Ioannis K. Kookos Frontmatter <u>More Information</u>

Preface xix

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.

Торіс	From the book	Hours
Introduction	Chapter 1	1
Review of unsteady-state material and energy	Chapter 2	1
balances		
Review of the Laplace transform	Appendix A	2
First-order systems	Chapter 3	5
Connections of first-order systems	Chapter 4	2
Second-order systems	Chapter 5	2
Higher-order systems	Chapter 6 and Appendix B (first half)	4 1/2
Eigenvalue analysis, asymptotic stability	Chapter 7 and Appendix B (second half)	2 1/2
Transfer-function analysis	Chapter 8	2
Bode diagrams	Chapter 9 – Bode part	1

#### xx Preface

Торіс	From the book	Hours
The feedback control system	Chapter 10	1
Block-diagram simplification, closed-loop	Chapter 11	2
Steady-state analysis, stability analysis	Chapter 12	2 1/2
State-space analysis of the closed-loop system	Chapter 13	1 1/2
Optimization of feedback controllers	Chapter 16	2
Systems with dead time	Chapter 14	2
Bode stability criterion, gain and phase	Chapter 17 – Bode part	1
margins Model based control	Charter 10 analysis a MIMO	2
Model-based control	Chapter 19, excluding MIMO	2
Cascade, ratio and feedforward control	Chapter 20	2
Total lecture hours		39

Costas Kravaris and Ioannis K. Kookos, October 2020