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978-1-107-03558-4 — Understanding Process Dynamics and Control
Costas Kravaris , Ioannis K. Kookos
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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.

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Dedicated to our families,

Irene, Michael, Evangeline and Cosmas
C. Kravaris

and

Natasa, Kostas and Georgia
I.K. Kookos

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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

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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

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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.

Topic	From the book	Hours
Introduction	Chapter 1	1
Review of unsteady-state material and energy balances	Chapter 2	1
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 ½
Eigenvalue analysis, asymptotic stability	Chapter 7 and Appendix B (second half)	2 ½
Transfer-function analysis	Chapter 8	2
Bode diagrams	Chapter 9 – Bode part	1

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Topic	From the book	Hours
The feedback control system	Chapter 10	1
Block-diagram simplification, closed-loop responses	Chapter 11	2
Steady-state analysis, stability analysis	Chapter 12	2 ½
State-space analysis of the closed-loop system	Chapter 13	1 ½
Optimization of feedback controllers	Chapter 16	2
Systems with dead time	Chapter 14	2
Bode stability criterion, gain and phase margins	Chapter 17 – Bode part	1
Model-based control	Chapter 19, excluding MIMO	2
Cascade, ratio and feedforward control	Chapter 20	2
Total lecture hours		39

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