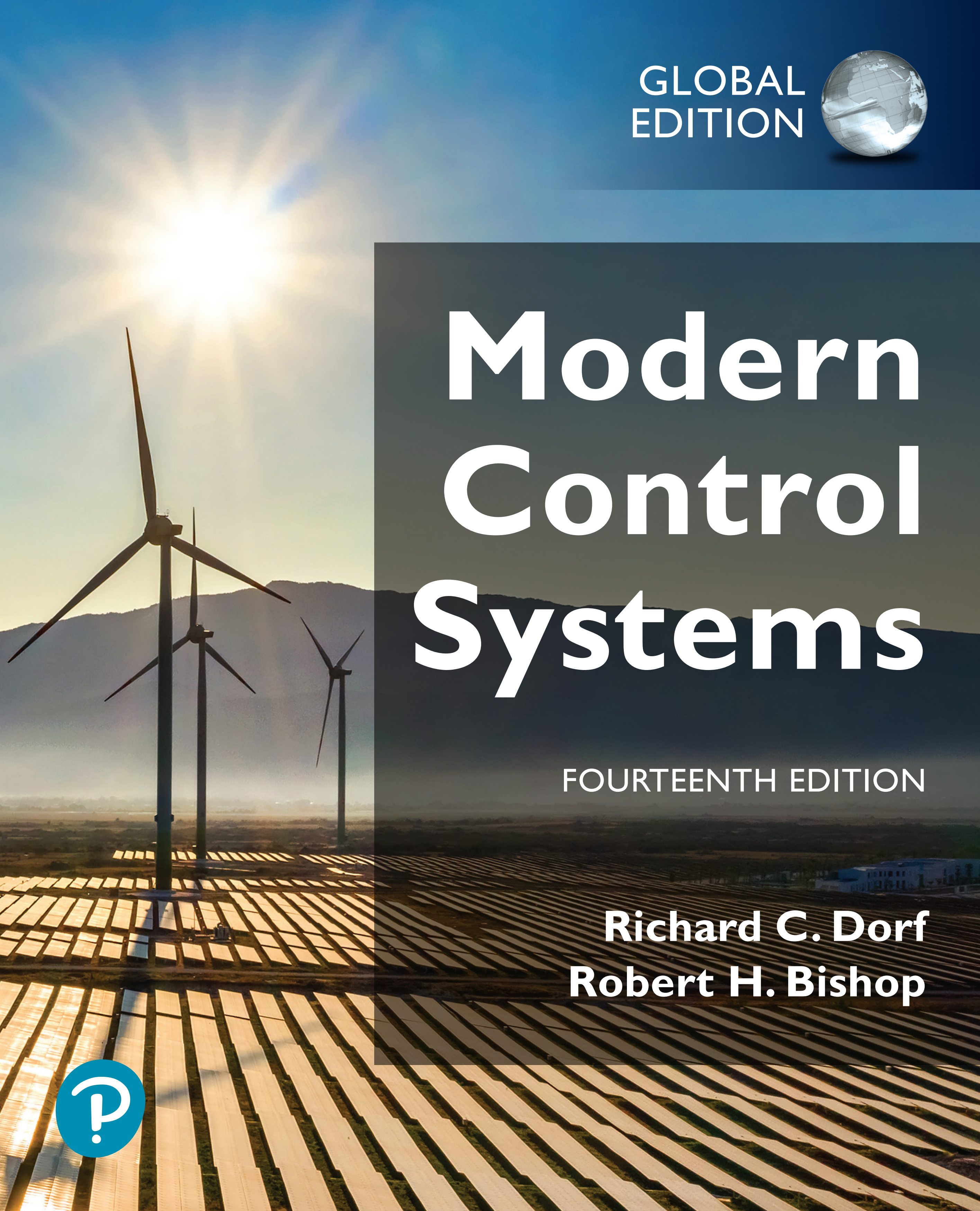


GLOBAL EDITION

Modern Control Systems

FOURTEENTH EDITION

Richard C. Dorf
Robert H. Bishop

Modern Control Systems

This page is intentionally left blank

Modern Control Systems

FOURTEENTH EDITION
GLOBAL EDITION

Richard C. Dorf
University of California, Davis

Robert H. Bishop
University of South Florida

Pearson

Please contact https://support.pearson.com/getsupport/s/ with any queries on this content.

Cover Image: Nguyen Quang Ngoc Tonkin/Shutterstock

Pearson Education Limited
KAO Two
KAO Park
Hockham Way
Harlow
CM17 9SR
United Kingdom

and Associated Companies throughout the world

Visit us on the World Wide Web at: www.pearsonglobaleditions.com

Authorized adaptation from the United States edition, entitled *Modern Control Systems*, 14th Edition, ISBN 978-0-13-730725-8 by Richard C. Dorf and Robert H. Bishop published by Pearson Education © 2022.

ISBN 10: 1-292-42237-8 (print)
ISBN 13: 978-1-292-42237-4 (print)
ISBN 13: 978-1-292-42235-0 (uPDF eBook)

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

eBook formatted by B2R Technologies Pvt. Ltd.

Dedicated to the memory of

Professor Richard C. Dorf

Brief Contents

Contents

CHAPTER 11 *The Design of State Variable Feedback Systems 812*

CHAPTER 12 *Robust Control Systems 882*

CHAPTER 13 *Digital Control Systems 945*

Preface

MODERN CONTROL SYSTEMS—THE BOOK

Global issues such as climate change, clean water, sustainability, pandemics, waste management, emissions reduction, and minimizing raw material and energy use have led many engineers to re-think existing approaches to engineering design. One outcome of the evolving design strategy is to consider *green engineering* and *human-centered design*. The goal of these approaches to engineering is to design products that minimize pollution, reduce the risk to human health, and improve the living environment. Applying the principles of green engineering and human-centered design highlights the power of feedback control systems as an enabling technology.

To reduce greenhouse gases and minimize pollution, it is necessary to improve both the quality and quantity of our environmental monitoring systems. One example is to use wireless measurements on mobile sensing platforms to measure the external environment. Another example is to monitor the quality of the delivered power to measure leading and lagging power, voltage variations, and waveform harmonics. Many green engineering systems and components require careful monitoring of current and voltages. For example, current transformers are used in various capacities for measuring and monitoring current within the power grid network of interconnected systems used to deliver electricity. Sensors are key components of any feedback control system because the measurements provide the required information as to the state of the system so the control system can take the appropriate action.

The role of control systems will continue to expand as the global issues facing us require ever increasing levels of automation and precision. In the book, we present key examples from green engineering such as wind turbine control and modeling of a photovoltaic generator for feedback control to achieve maximum power delivery as the sunlight varies over time.

The wind and sun are important sources of renewable energy around the world. Wind energy conversion to electric power is achieved by wind energy turbines connected to electric generators. The intermittency characteristic of the wind makes smart grid development essential to bring the energy to the power grid when it is available and to provide energy from other sources when the wind dies down or is disrupted. A smart grid can be viewed as a system comprised of hardware and software that routes power more reliably and efficiently to homes, businesses, schools, and other users of power in the presence of intermittency and other disturbances. The irregular character of wind direction and power also results in the need for reliable, steady electric energy by using control systems on the wind turbines themselves. The goal of these control devices is to reduce the effects of wind intermittency and the effect of wind direction change. Energy storage systems are also critical technologies for green engineering. We seek energy storage systems that are renewable, such as fuel cells. Active control can be a key element of effective renewable energy storage systems as well.

Another exciting development for control systems is the evolution of the Internet of Things—a network of physical objects embedded with electronics, software, sensors and connectivity. As envisioned, each of the millions of the devices on the network will possess an embedded computer with connectivity to the Internet. The ability to control these connected devices will be of great interest to control engineers. Indeed, control engineering is an exciting and a challenging field. By its very nature, control engineering is a multidisciplinary subject, and it has taken its place as a core course in the engineering curriculum. It is reasonable to expect different approaches to mastering and practicing the art of control engineering. Since the subject has a strong mathematical foundation, we might approach it from a strictly theoretical point of view, emphasizing theorems and proofs. On the other hand, since the ultimate objective is to implement controllers in real systems, we might take an ad hoc approach relying only on intuition and hands-on experience when designing feedback control systems. Our approach is to present a control engineering methodology that, while based on mathematical fundamentals, stresses physical system modeling and practical control system designs with realistic system specifications.

We believe that the most important and productive approach to learning is for each of us to rediscover and re-create anew the answers and methods of the past. Thus, the ideal is to present the student with a series of problems and questions and point to some of the answers that have been obtained over the past decades. The traditional method—to confront the student not with the problem but with the finished solution—is to deprive the student of all excitement, to shut off the creative impulse, to reduce the adventure of humankind to a dusty heap of theorems. The issue, then, is to present some of the unanswered and important problems that we continue to confront, for it may be asserted that what we have truly learned and understood, we discovered ourselves.

The purpose of this book is to present the structure of feedback control theory and to provide a sequence of exciting discoveries as we proceed through the text and problems. If this book is able to assist the student in discovering feedback control system theory and practice, it will have succeeded.

WHAT'S NEW IN THIS EDITION

This latest edition of *Modern Control Systems* incorporates the following key updates:

- Available as both an eText and print book.
- Video solutions for select problems throughout the text.
- Interactive figures added throughout the eText to enhance student learning.
- In the eText, interactive Skills Check multiple-choice questions at the end of each chapter.
- Over 20% new or updated problems. There are over 980 end-of-chapter exercises, problems, advanced problems, design problems, and computer problems.
- Expanded use of color for clarity of presentation.
- An updated companion website available at www.pearsonglobaleditions.com for students and faculty.

THE AUDIENCE

This text is designed for an introductory undergraduate course in control systems for engineering students. There is very little demarcation between the various engineering areas in control system practice; therefore, this text is written without any conscious bias toward one discipline. Thus, it is hoped that this book will be equally useful for all engineering disciplines and, perhaps, will assist in illustrating the utility of control engineering. The numerous problems and examples represent all fields, and the examples of the sociological, biological, ecological, and economic control systems are intended to provide the reader with an awareness of the general applicability of control theory to many facets of life. We believe that exposing students of one discipline to examples and problems from other disciplines will provide them with the ability to see beyond their own field of study. Many students pursue careers in engineering fields other than their own. We hope this introduction to control engineering will give students a broader understanding of control system design and analysis.

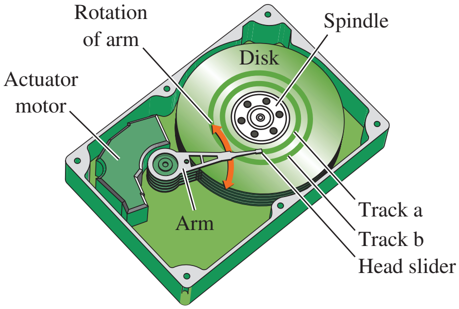
In its first thirteen editions, *Modern Control Systems* has been used in senior-level courses for engineering students at many colleges and universities globally. It also has been used in courses for engineering graduate students with no previous background in control engineering.

THE FOURTEENTH EDITION

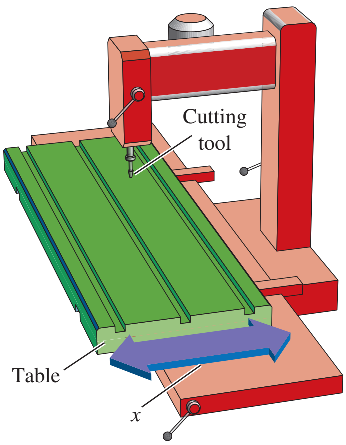
With the fourteenth edition, we have created an interactive e-textbook to fully use rich, digital content for *Modern Control Systems* to enhance the learning experience. This version contains embedded videos, dynamic graphs, live Skills Check quizzes, and active links to additional resources. The electronic version provides a powerful interactive experience that would be difficult, if not impossible, to achieve in a print book.

A companion website is also available to students and faculty using the fourteenth edition. The website contains many resources, including the m-files in the book, Laplace and z-Transform tables, written materials on matrix algebra and complex numbers, symbols, units, and conversion factors, and an introduction to MATLAB and to the LabVIEW MathScript RT Module. The MCS website is available at www.pearsonglobaleditions.com.

We continue the design emphasis that historically has characterized *Modern Control Systems*. Using the real-world engineering problems associated with designing a controller for a disk drive read system, we present the *Sequential Design Example*, which is considered sequentially in each chapter using the methods and concepts in that chapter. Disk drives are used in computers of all sizes and they represent an important application of control engineering. Various aspects of the design of controllers for the disk drive read system are considered in each chapter. For example, in Chapter 1 we identify the control goals, identify the variables to be controlled, write the control specifications, and establish the preliminary system configuration for the disk drive. Then, in Chapter 2, we obtain models of the process, sensors, and actuators. In the remaining chapters, we continue the design process, stressing the main points of the chapters.



In the same spirit as the *Sequential Design Example*, we present a design problem that we call the *Continuous Design Problem* to give students the opportunity to build upon a design problem from chapter to chapter. High-precision machinery places stringent demands on table slide systems. In the *Continuous Design Problem*, students apply the techniques and tools presented in each chapter to the development of a design solution that meets the specified requirements.



The computer-aided design and analysis component of the book continues to evolve and improve. Also, many of the solutions to various components of the *Sequential Design Example* utilize m-files with corresponding scripts included in the figures.

A Skills Check section is included at the end of each chapter. In each Skills Check section, we provide three sets of problems to test your knowledge of the chapter material. This includes True or False, Multiple Choice, and Word Match problems. To obtain direct feedback, you can check your answers with the answer key provided at the conclusion of the end-of-chapter problems.

PEDAGOGY

The book is organized around the concepts of control system theory as they have been developed in the frequency and time domains. An attempt has been made to make the selection of topics, as well as the systems discussed in the examples and problems, modern in the best sense. Therefore, this book includes discussions on robust control systems and system sensitivity, state variable models, controllability and observability, computer control systems, internal model control, robust PID controllers, and computer-aided design and analysis, to name a few. However, the classical topics of control theory that have proved to be so very useful in practice have been retained and expanded.

Building Basic Principles: From Classical to Modern. Our goal is to present a clear exposition of the basic principles of frequency and time-domain design techniques. The classical methods of control engineering are thoroughly covered: Laplace transforms and transfer functions; root locus design; Routh–Hurwitz stability analysis; frequency response methods, including Bode, Nyquist, and Nichols; steady-state error for standard test signals; second-order system approximations; and phase and gain margin and bandwidth. In addition, coverage of the state variable method is significant. Fundamental notions of controllability and observability for state variable models are discussed. Full state feedback design with Ackermann's formula for pole placement is presented, along with a discussion on the limitations of state variable feedback. Observers are introduced as a means to provide state estimates when the complete state is not measured.

Upon this strong foundation of basic principles, the book provides many opportunities to explore topics beyond the traditional. In the latter chapters, we present introductions into more advanced topics of robust control and digital control, as well as an entire chapter devoted to the design of feedback control systems with a focus on practical industrial lead and lag compensator structures. Problem solving is emphasized throughout the chapters. Each chapter (but the first) introduces the student to the notion of computer-aided design and analysis.

Progressive Development of Problem-Solving Skills. Reading the chapters, attending lectures and taking notes, and working through the illustrated examples are all part of the learning process. But the real test comes at the end of the chapter with the problems. The book takes the issue of problem solving seriously. In each chapter, there are five problem types:

- Exercises
- Problems
- Advanced Problems
- Design Problems
- Computer Problems

For example, the problem set for Mathematical Models of Systems, Chapter 2 includes 31 exercises, 51 problems, 9 advanced problems, 6 design problems, and

10 computer-based problems. The exercises permit the students to readily utilize the concepts and methods introduced in each chapter by solving relatively straightforward exercises before attempting the more complex problems. The problems require an extension of the concepts of the chapter to new situations. The advanced problems represent problems of increasing complexity. The design problems emphasize the design task; the computer-based problems give the student practice with problem solving using computers. In total, the book contains more than 980 problems. The abundance of problems of increasing complexity gives students confidence in their problem solving ability as they work their way from the exercises to the design and computer-based problems. An instructor's manual, available to all adopters of the text for course use, contains complete solutions to all end-of-chapter problems.

A set of m-files, the *Modern Control Systems Toolbox*, has been developed by the authors to supplement the text. The m-files contain the scripts from each computer-based example in the text. You may retrieve the m-files from the companion available at www.pearsonglobaleditions.com.

Design Emphasis without Compromising Basic Principles. The all-important topic of design of real-world, complex control systems is a major theme throughout the text. Emphasis on design for real-world applications addresses interest in design by ABET and industry.

The design process consists of seven main building blocks that we arrange into three groups:

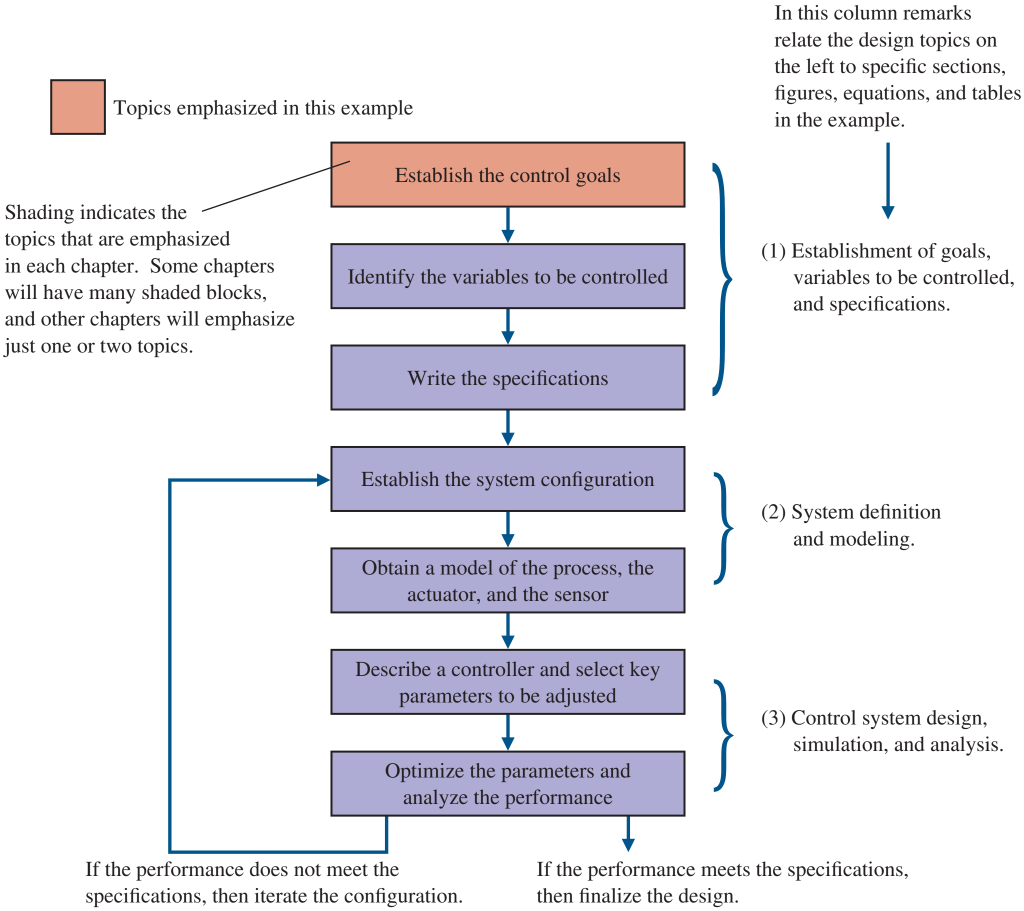
1. Establishment of goals and variables to be controlled, and definition of specifications (metrics) against which to measure performance
2. System definition and modeling
3. Control system design and integrated system simulation and analysis

In each chapter of this book, we highlight the connection between the design process and the main topics of that chapter. The objective is to demonstrate different aspects of the design process through illustrative examples.

Various aspects of the control system design process are illustrated in detail in many examples across all the chapters, including applications of control design in robotics, manufacturing, medicine, and transportation (ground, air, and space).

Each chapter includes a section to assist students in utilizing computer-aided design and analysis concepts and in reworking many of the design examples. Generally, m-files scripts are provided that can be used in the design and analyses of the feedback control systems. Each script is annotated with comment boxes that highlight important aspects of the script. The accompanying output of the script (generally a graph) also contains comment boxes pointing out significant elements. The scripts can also be utilized with modifications as the foundation for solving other related problems.

Learning Enhancement. Each chapter begins with a chapter preview describing the topics the student can expect to encounter. The chapters conclude with an end-of-chapter summary, skills check, as well as terms and concepts. These sections

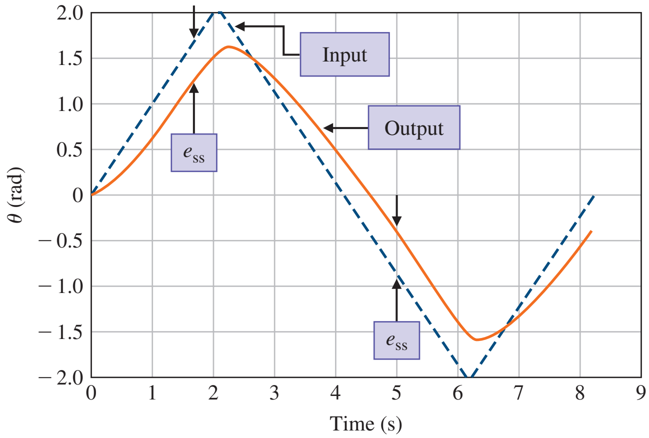


reinforce the important concepts introduced in the chapter and serve as a reference for later use.

Color is used to add emphasis when needed and to make the graphs and figures easier to interpret. For example, consider the computer control of a robot to spray-paint an automobile. We might ask the student to investigate the closed-loop system stability for various values of the controller gain K and to determine the response to a unit step disturbance, $T_d(s) = 1/s$, when the input $R(s) = 0$. The associated figure assists the student with (a) visualizing the problem, and (b) taking the next step to develop the transfer function model and to complete the analyses.

THE ORGANIZATION

Chapter 1 Introduction to Control Systems. Chapter 1 provides an introduction to the basic history of control theory and practice. The purpose of this chapter is to describe the general approach to designing and building a control system.



(a)

```
%Compute the response of the Mobile Robot Control
%System to a triangular wave input
%
numg=[10 20]; deng=[1 10 0]; sysg=tf(numg,deng);
[sys]=feedback(sysg, [1]);
t=[0:0.1:8.2]';
v1=[0:0.1:2]';v2=[2:-0.1:-2]';v3=[-2:0.1:0]';
u=[v1;v2;v3];
[y,T]=lsim(sys,u,t);
plot(T,y,t,u,'--'),
xlabel('Time (s)'), ylabel('\theta (rad)'), grid
```

$G(s)G_c(s)$

Compute triangular wave input.

Linear simulation.

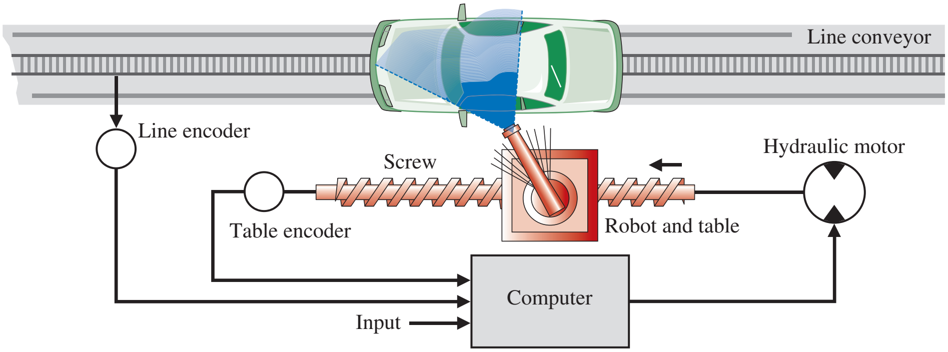
(b)

Chapter 2 Mathematical Models of Systems. Mathematical models of physical systems in input–output or transfer function form are developed in Chapter 2. A wide range of systems are considered.

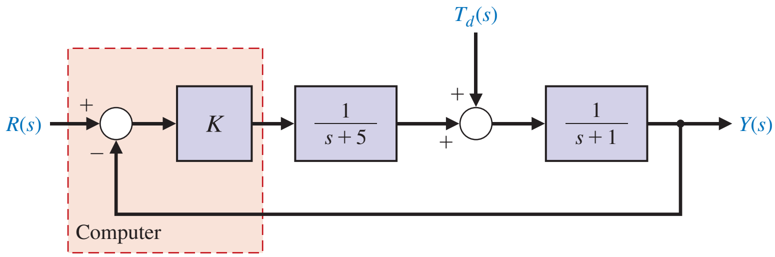
Chapter 3 State Variable Models. Mathematical models of systems in state variable form are developed in Chapter 3. The transient response of control systems and the performance of these systems are examined.

Chapter 4 Feedback Control System Characteristics. The characteristics of feedback control systems are described in Chapter 4. The advantages of feedback are discussed, and the concept of the system error signal is introduced.

Chapter 5 The Performance of Feedback Control Systems. In Chapter 5, the performance of control systems is examined. The performance of a control system is correlated with the s-plane location of the poles and zeros of the transfer function of the system.



(a)



(b)

Chapter 6 The Stability of Linear Feedback Systems. The stability of feedback systems is investigated in Chapter 6. The relationship of system stability to the characteristic equation of the system transfer function is studied. The Routh–Hurwitz stability criterion is introduced.

Chapter 7 The Root Locus Method. Chapter 7 deals with the motion of the roots of the characteristic equation in the s-plane as one or two parameters are varied. The locus of roots in the s-plane is determined by a graphical method. We also introduce the popular PID controller and the Ziegler-Nichols PID tuning method.

Chapter 8 Frequency Response Methods. In Chapter 8, a steady-state sinusoid input signal is utilized to examine the steady-state response of the system as the frequency of the sinusoid is varied. The development of the frequency response plot, called the Bode plot, is considered.

Chapter 9 Stability in the Frequency Domain. System stability utilizing frequency response methods is investigated in Chapter 9. Relative stability and the Nyquist criterion are discussed. Stability is considered using Nyquist plots, Bode plots, and Nichols charts.

Chapter 10 The Design of Feedback Control Systems. Several approaches to designing and compensating a control system are described and developed in Chapter 10. Various candidates for service as compensators are presented and it is shown how they help to achieve improved performance. The focus is on lead and lag compensators.

Chapter 11 The Design of State Variable Feedback Systems. The main topic of Chapter 11 is the design of control systems using state variable models. Full-state feedback design and observer design methods based on pole placement are discussed. Tests for controllability and observability are presented, and the concept of an internal model design is discussed.

Chapter 12 Robust Control Systems. Chapter 12 deals with the design of highly accurate control systems in the presence of significant uncertainty. Five methods for robust design are discussed, including root locus, frequency response, ITAE methods for robust PID controllers, internal models, and pseudo-quantitative feedback.

Chapter 13 Digital Control Systems. Methods for describing and analyzing the performance of computer control systems are described in Chapter 13. The stability and performance of sampled-data systems are discussed.

ACKNOWLEDGMENTS

We wish to express our sincere appreciation to the following individuals who have assisted us with the development of this Fourteenth edition, as well as all previous editions: John Hung, Auburn University; Zak Kassas, University of California-Irvine; Hanz Richter, Cleveland State Universtiy; Abhishek Gupta, The Ohio State University; Darris White, Embry Riddle Aeronautical University; John K. Schueller, University of Florida; Mahmoud A. Abdallah, Central Sate University (OH); John N. Chiasson, University of Pittsburgh; Samy El-Sawah, California State Polytechnic University, Pomona; Peter J. Gorder, Kansas State University; Duane Hanselman, University of Maine; Ashok Iyer, University of Nevada, Las Vegas; Leslie R. Koval, University of Missouri-Rolla; L. G. Kraft, University of New Hampshire; Thomas Kurfess, Georgia Institute of Technology; Julio C. Mandojana, Mankato State University; Luigi Mariani, University of Padova; Jure Medanic, University of Illinois at Urbana- Champaign; Eduardo A. Misawa, Oklahoma State University; Medhat M. Morcos, Kansas State University; Mark Nagurka, Marquette University; D. Subbaram Naidu, Idaho State University; Ron Perez, University of Wisconsin-Milwaukee; Carla Schwartz, The MathWorks, Inc.; Murat Tanyel, Dordt College; Hal Tharp, University of Arizona; John Valasek, Texas A & M University; Paul P. Wang, Duke University; and Ravi Warrier, GMI Engineering and Management Institute. Special thanks to Greg Mason, Seattle University, and Jonathan Sprinkle, University of Arizona, for developing the interactives and the video solutions.

ACKNOWLEDGMENTS FOR THE GLOBAL EDITION

Pearson would like to acknowledge and thank the following for the Global Edition:

CONTRIBUTORS

Benjamin Chong, University of Leeds
Murat Doğruel, Marmara University
Quang Ha, University of Technology Sydney
Ashish Rajeshwar Kulkarni, Delhi Technological University
Savita Nema, Maulana Azad National Institute of Technology Bhopal
Mark Ovinis, Universiti Teknologi PETRONAS
Bidyadhar Subudhi, National Institute of Technology Rourkela

REVIEWERS

Quang Ha, University of Technology Sydney
Shen Hin Lim, University of Waikato
Mark Ovinis, Universiti Teknologi PETRONAS
Fuwen Yang, Griffith University

OPEN LINES OF COMMUNICATION

The authors would like to establish a line of communication with the users of *Modern Control Systems*. We encourage all readers to send comments and suggestions for this and future editions. By doing this, we can keep you informed of any general-interest news regarding the textbook and pass along comments of other users.

Keep in touch!

Robert H. Bishop robertbishop@usf.edu

About the Authors

Richard C. Dorf was Emeriti Faculty of Electrical and Computer Engineering at the University of California, Davis. Known as an instructor who was highly concerned with the discipline of electrical engineering and its application to social and economic needs, Professor Dorf wrote and edited several successful engineering textbooks and handbooks, including the best selling *Engineering Handbook*, second edition and the third edition of the *Electrical Engineering Handbook*. Professor Dorf was also co-author of *Technology Ventures*, a leading textbook on technology entrepreneurship. Professor Dorf was a Fellow of the IEEE and a Fellow of the ASEE. Dr. Dorf held a patent for the PIDA controller.

Robert H. Bishop is the Dean of Engineering at the University of South Florida, President and CEO of the Institute of Applied Engineering, and a Professor in the Department of Electrical Engineering. Prior to coming to The University of South Florida, he was the Dean of Engineering at Marquette University and before that a Department Chair and Professor of Aerospace Engineering and Engineering Mechanics at The University of Texas at Austin where he held the Joe J. King Professorship and was a Distinguished Teaching Professor. Professor Bishop started his engineering career as a member of the technical staff at the Charles Stark Draper Laboratory. He authors the well-known textbook for teaching graphical programming entitled *Learning with LabVIEW* and is also the editor-in-chief of the *Mechatronics Handbook*. Professor Bishop remains an active teacher and researcher and has authored/co-authored over one hundred and forty-five journal and conference papers. He is a Fellow of the AIAA, a Fellow of the American Astronautical Society (AAS), a Fellow of the American Association for the Advancement of Science (AAAS) and active in ASEE and in the Institute of Electrical and Electronics Engineers (IEEE).

CHAPTER 1

Introduction to Control Systems

PREVIEW

A control system consists of interconnected components to achieve a desired purpose. In this chapter, we discuss open- and closed-loop feedback control systems. We examine examples of control systems through the course of history. Early systems incorporated many of the basic ideas of feedback that are employed in modern control systems. A design process is presented that encompasses the establishment of goals and variables to be controlled, definition of specifications, system definition, modeling, and analysis. The iterative nature of design allows us to handle the design gap effectively while accomplishing necessary trade-offs in complexity, performance, and cost. Finally, we introduce the Sequential Design Example: Disk Drive Read System. This example will be considered sequentially in each chapter of this book. It represents a practical control system design problem while simultaneously serving as a useful learning tool.

DESIRED OUTCOMES

Upon completion of Chapter 1, students should be able to:

- ❑ Give illustrative examples of control systems and describe their relationship to key contemporary issues.
- ❑ Recount a brief history of control systems and their role in society.
- ❑ Predict the future of controls in the context of their evolutionary pathways.
- ❑ Recognize the elements of control system design and possess an appreciation of appreciate controls in the context of engineering design.

1.1 INTRODUCTION

Engineers create products that help people. Our quality of life is sustained and enhanced through engineering. To accomplish this, engineers strive to understand, model, and control the materials and forces of nature for the benefit of humankind. A key area of engineering that reaches across many technical areas is the multidisciplinary field of control system engineering. Control engineers are concerned with understanding and controlling segments of their environment, often called **systems**, which are interconnections of elements and devices for a desired purpose. The system might be something as clear-cut as an automobile cruise control system, or as extensive and complex as a direct brain-to-computer system to control a manipulator. Control engineering deals with the design (and implementation) of control systems using linear, time-invariant mathematical models representing actual physical nonlinear, time-varying systems with parameter uncertainties in the presence of external disturbances. As computer systems—especially embedded processors—have become less expensive, require less power and space, while growing more computationally powerful, at the same time that sensors and actuators have simultaneously experienced the same evolution to more capability in smaller packages, the application of control systems has grown in number and complexity. A **sensor** is a device that provides a measurement of a desired external signal. For example, resistance temperature detectors (RTDs) are sensors used to measure temperature. An **actuator** is a device employed by the control system to alter or adjust the environment. An electric motor drive used to rotate a robotic manipulator is an example of a device transforming electric energy to mechanical torque.

The face of control engineering is rapidly changing. The age of the Internet of Things (IoT) presents many intriguing challenges in control system applications in the environment (think about more efficient energy use in homes and businesses), manufacturing (think 3D printing), consumer products, energy, medical devices and healthcare, transportation (think about automated cars!), among many others [14]. A challenge for control engineers today is to be able to create simple, yet reliable and accurate mathematical models of many of our modern, complex, interrelated, and interconnected systems. Fortunately, many modern design tools are available, as well as open source software modules and Internet-based user groups (to share ideas and answer questions), to assist the modeler. The implementation of the control systems themselves is also becoming more automated, again assisted by many resources readily available on the Internet coupled with access to relatively inexpensive computers, sensors, and actuators. **Control system engineering** focuses on the modeling of a wide assortment of physical systems and using those models to design controllers that will cause the closed-loop systems to possess desired performance characteristics, such as stability, relative stability, steady-state tracking with prescribed maximum errors, transient tracking (percent overshoot, settling time, rise time, and time to peak), rejection of external disturbances, and robustness to modeling uncertainties. The extremely important step of the overall design and implementation process is designing the control systems, such as PID controllers, lead and lag controllers, state variable feedback controllers, and other popular controller structures. That is what this textbook is all about!