Modern Control Systems

Thirteenth Edition

Richard C. Dorf | Robert H. Bishop

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THIRTEENTH EDITION

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Of the greater teachers—
when they are gone,
their students will say:
we did it ourselves.

Dedicated to

Lynda Ferrera Bishop

and

Joy MacDonald Dorf

In grateful appreciation

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Brief Contents

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WEB RESOURCES

Preface

MODERN CONTROL SYSTEMS—THE BOOK

Global issues such as climate change, clean water, sustainability, 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*. The goal of green engineering is to design products that minimize pollution, reduce the risk to human health, and improve the environment. Applying the principles of green engineering 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 in green engineering 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:

- An interactive e-textbook version is now available.
- Updated companion website www.pearsonhighered.com/dorf for students and faculty.
- Over 20% of the problems updated or newly added. There are 980 end-of-chapter exercises, problems, advanced problems, design problems, and computer problems. Instructors will have no difficulty finding different problems to assign semester after semester.
- The design process of lead and lag compensators in Chapter 10 has been updated for ease of understanding and consistency of nomenclature.
- The textbook has been streamlined for clarity of presentation.

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.

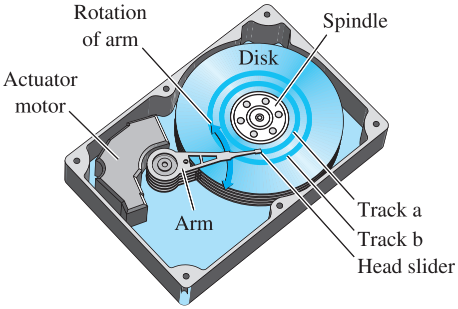
In its first twelve editions, *Modern Control Systems* has been used in senior-level courses for engineering students at many colleges and universities globally. It also has been used in courses for engineering graduate students with no previous background in control engineering.

THE THIRTEENTH EDITION

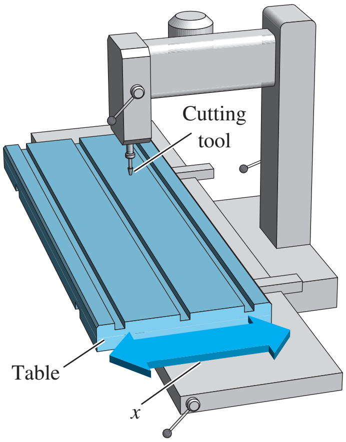
With the thirteenth edition, we have created an interactive e-textbook to fully use rich, digital content for *Modern Control Systems* to enhance the learning experience. This version contains embedded videos, dynamic graphs, live Skills Check quizzes, and active links to additional resources. The electronic 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 thirteenth 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. An icon will appear in the book margin whenever there is additional related material on the website. The MCS website address is www.pearsonhighered.com/dorf.

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 of 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 Frequency Response Methods, Chapter 8 includes 15 exercises, 27 problems, 7 advanced problems, 7 design problems, and

9 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. Answers to one-third of the exercises are provided. 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 website: www.pearsonhighered.com/dorf.

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:

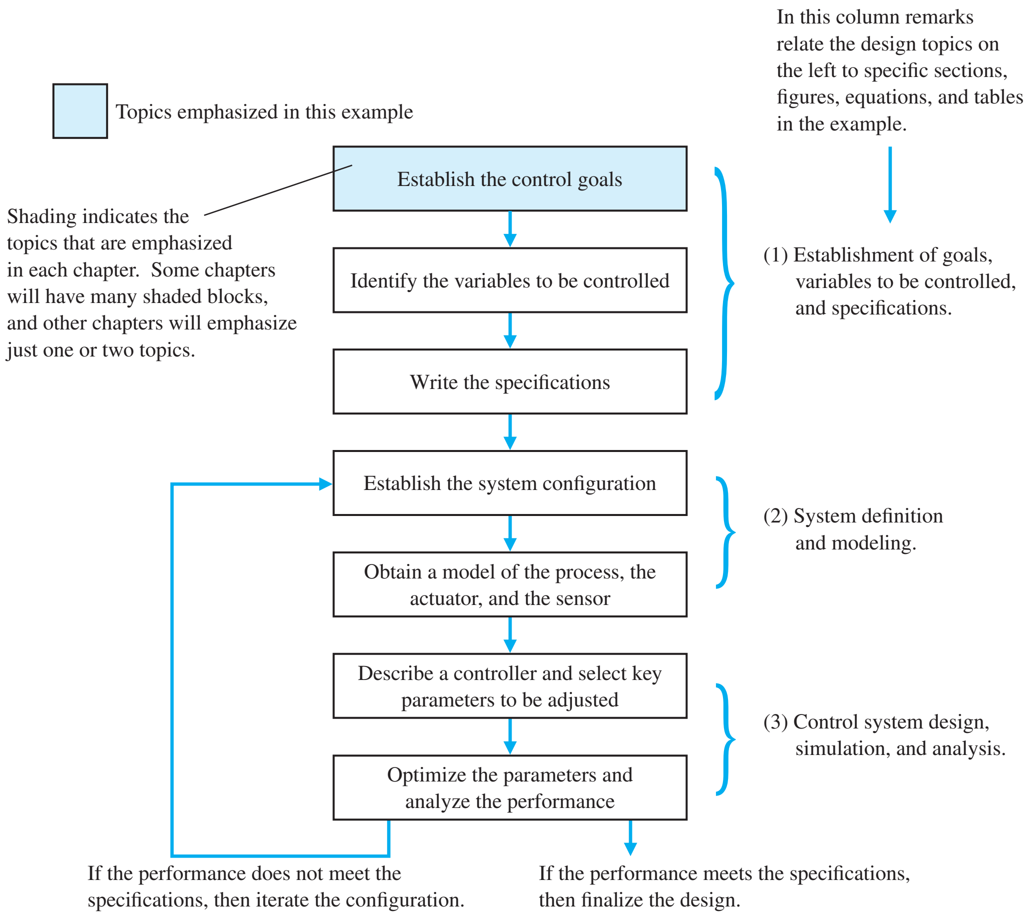
1. Establishment of goals and variables to be controlled, and definition of specifications (metrics) against which to measure performance
2. System definition and modeling
3. Control system design and integrated system simulation and analysis

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

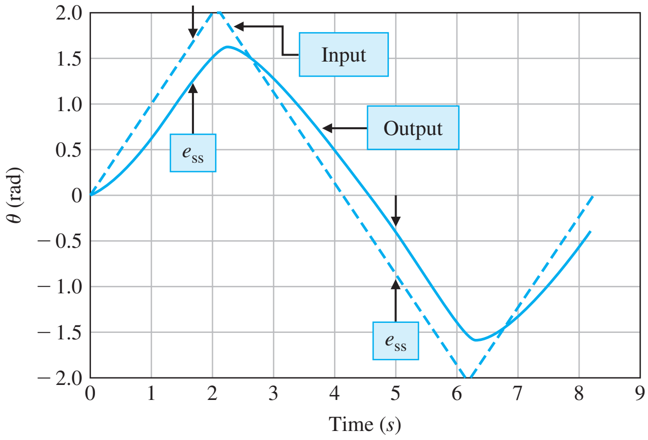


reinforce the important concepts introduced in the chapter and serve as a reference for later use.

A second 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.

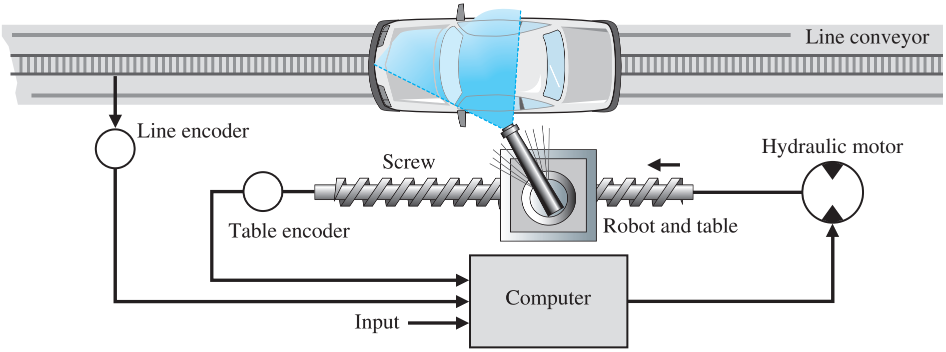
(b)

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.

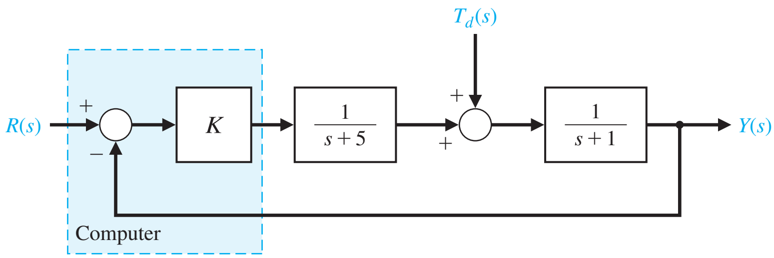
Chapter 3 State Variable Models. Mathematical models of systems in state variable form are developed in Chapter 3. The transient response of control systems and the performance of these systems are examined.

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 thirteenth edition, as well as all previous editions: 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.

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!

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About the Authors

Richard C. Dorf is a Professor of Electrical and Computer Engineering at the University of California, Davis. Known as an instructor who is highly concerned with the discipline of electrical engineering and its application to social and economic needs, Professor Dorf has written 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 is also co-author of *Technology Ventures*, a leading textbook on technology entrepreneurship. Professor Dorf is a Fellow of the IEEE and a Fellow of the ASEE. He is active in the fields of control system design and robotics. Dr. Dorf holds a patent for the PIDA controller.

Robert H. Bishop is the Dean of Engineering at the University of South Florida and is 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 thirty-five journal and conference papers. He is an active member of the Global Engineering Deans Council that seeks to establish a global network of engineering deans for the advancement of engineering education, research and service to the global community. He is a Fellow of the AIAA, a Fellow of the American Astronautical Society (AAS), and active in ASEE and in the Institute of Electrical and Electronics Engineers (IEEE).

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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:

- Possess a basic understanding of control system engineering and be able to offer some illustrative examples and their relationship to key contemporary issues.
- Be able to recount a brief history of control systems and their role in society.
- Be capable of discussing the future of controls in the context of their evolutionary pathways.
- Recognize the elements of control system design and possess an appreciation of 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 coming 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—both professional and student versions—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!

FIGURE 1.1 Process to be controlled.

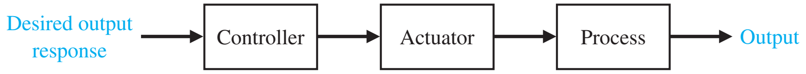

FIGURE 1.2 Open-loop control system (without feedback).

Control system engineering is based on the foundations of feedback theory and linear system analysis, and it integrates the concepts of network theory and communication theory. It possesses a strong mathematical foundation, yet is very practical and impacts our lives every day in almost all we do. Indeed, control engineering is not limited to any engineering discipline but is equally applicable to aerospace, agricultural, biomedical, chemical, civil, computer, industrial, electrical, environmental, mechanical, and nuclear engineering. Many aspects of control engineering can also be found in studies in systems engineering.

A **control system** is an interconnection of components forming a system configuration that will provide a desired system response. The basis for analysis of a system is the foundation provided by linear system theory, which assumes a cause–effect relationship for the components of a system. A component, or **process**, to be controlled can be represented graphically, as shown in Figure 1.1. The input–output relationship represents the cause-and-effect relationship of the process, which in turn represents a processing of the input signal to provide a desired output signal. An **open-loop control system** uses a controller and an actuator to obtain the desired response, as shown in Figure 1.2. An open-loop system is a system without feedback.

An open-loop control system utilizes an actuating device to control the process directly without using feedback.

In contrast to an open-loop control system, a closed-loop control system utilizes an additional measure of the actual output to compare the actual output with the desired output response. The measure of the output is called the **feedback signal**. A simple **closed-loop feedback control system** is shown in Figure 1.3. A feedback control system is a control system that tends to maintain a prescribed relationship of one system variable to another by comparing functions of these variables and using the difference as a means of control. With an accurate sensor, the measured output is a good approximation of the actual output of the system.

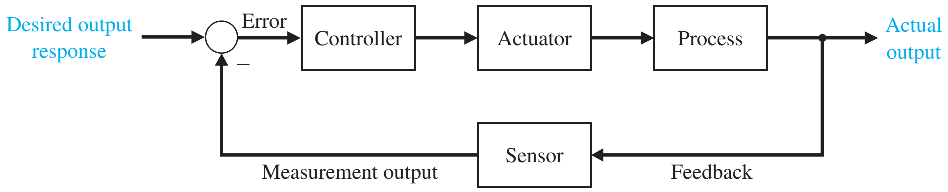

FIGURE 1.3 Closed-loop feedback control system (with feedback).

A feedback control system often uses a function of a prescribed relationship between the output and reference input to control the process. Often the difference between the output of the process under control and the reference input is amplified and used to control the process so that the difference is continually reduced. In general, the difference between the desired output and the actual output is equal to the error, which is then adjusted by the controller. The output of the controller causes the actuator to modulate the process in order to reduce the error. The sequence is such, for instance, that if a ship is heading incorrectly to the right, the rudder is actuated to direct the ship to the left. The system shown in Figure 1.3 is a **negative feedback** control system, because the output is subtracted from the input and the difference is used as the input signal to the controller. The feedback concept has been the foundation for control system analysis and design.

A closed-loop control system uses a measurement of the output and feedback of this signal to compare it with the desired output (reference or command).

As we will discuss in Chapter 4, closed-loop control has many advantages over open-loop control including the ability to reject external **disturbances** and improve **measurement noise** attenuation. We incorporate the disturbances and measurement noise in the block diagram as external inputs, as illustrated in Figure 1.4. External disturbances and measurement noise are inevitable in real-world applications and must be addressed in practical control system designs.

The feedback systems in Figures 1.3 and 1.4 are single-loop feedback systems. Many feedback control systems contain more than one feedback loop. A common **multiloop feedback control system** is illustrated in Figure 1.5 with an inner loop and an outer loop. In this scenario, the inner loop has a controller and a sensor and the outer loop has a controller and sensor. Other varieties of multiloop feedback systems are considered throughout the book as they represent more practical situations found in real-world applications. However, we use the single-loop feedback system for learning about the benefits of feedback control systems since the outcomes readily extend to multiloop systems.

Due to the increasing complexity of the system under control and the interest in achieving optimum performance, the importance of control system engineering has grown in the past decade. Furthermore, as the systems become more complex, the interrelationship of many controlled variables must be considered in the control scheme. A block diagram depicting a **multivariable control system** is shown in Figure 1.6.

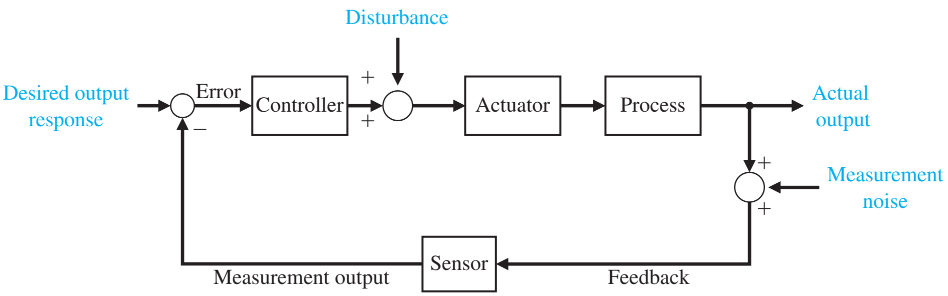

FIGURE 1.4 Closed-loop feedback system with external disturbances and measurement noise.

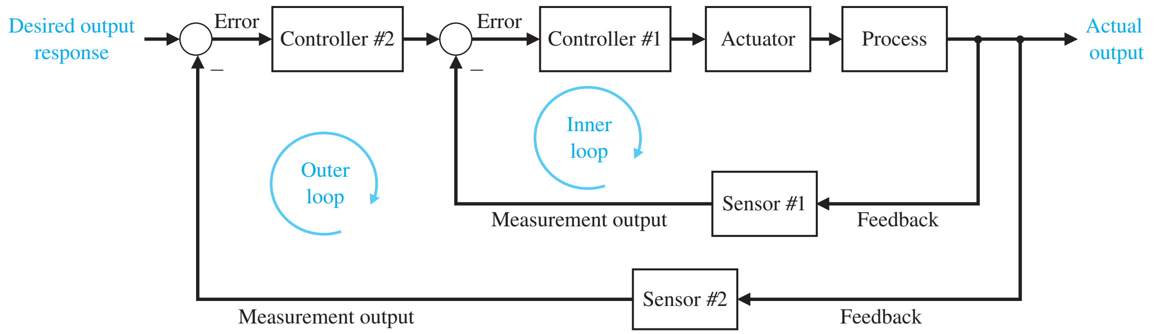

FIGURE 1.5 Multiloop feedback system with an inner loop and an outer loop.

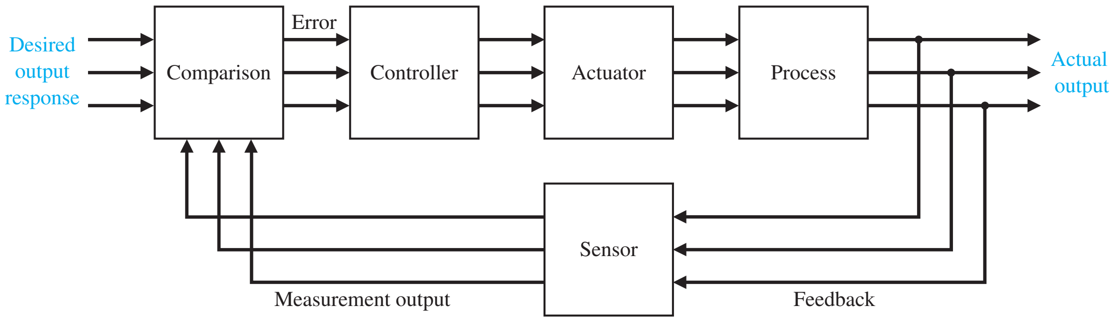

FIGURE 1.6 Multivariable control system.

A common example of an open-loop control system is a microwave oven set to operate for a fixed time. An example of a closed-loop control system is a person steering an automobile (assuming his or her eyes are open) by looking at the auto's location on the road and making the appropriate adjustments.

The introduction of feedback enables us to control a desired output and can improve accuracy, but it requires attention to the issue of stability of response.

1.2 BRIEF HISTORY OF AUTOMATIC CONTROL

The use of feedback to control a system has a fascinating history. The first applications of feedback control appeared in the development of float regulator mechanisms in Greece in the period 300 to 1 b.c. [1, 2, 3]. The water clock of Ktesibios used a float regulator (refer to Problem P1.11). An oil lamp devised by Philon in approximately 250 b.c. used a float regulator in an oil lamp for maintaining a constant level of fuel oil. Heron of Alexandria, who lived in the first century a.d., published a book entitled *Pneumatica*, which outlined several forms of water-level mechanisms using float regulators [1].

The first feedback system to be invented in modern Europe was the temperature regulator of Cornelis Drebbel (1572–1633) of Holland [1]. Dennis Papin

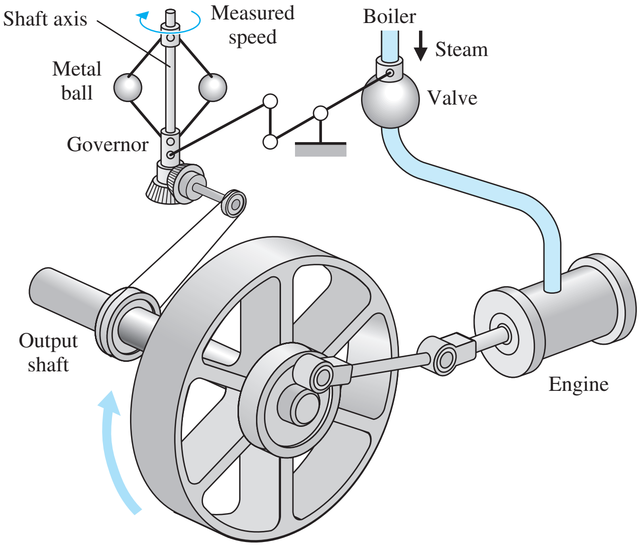

FIGURE 1.7 Watt's flyball governor.

(1647–1712) invented the first pressure regulator for steam boilers in 1681. Papin's pressure regulator was a form of safety regulator similar to a pressure-cooker valve.

The first automatic feedback controller used in an industrial process is generally agreed to be James Watt's **flyball governor**, developed in 1769 for controlling the speed of a steam engine [1, 2]. The all-mechanical device, shown in Figure 1.7, measured the speed of the output shaft and utilized the movement of the flyball to control the steam valve and therefore the amount of steam entering the engine. As depicted in Figure 1.7, the governor shaft axis is connected via mechanical linkages and beveled gears to the output shaft of the steam engine. As the steam engine output shaft speed increases, the ball weights rise and move away from the shaft axis and through mechanical linkages the steam valve closes and the engine slows down.

The first historical feedback system, claimed by Russia, is the water-level float regulator said to have been invented by I. Polzunov in 1765 [4]. The level regulator system is shown in Figure 1.8. The float detects the water level and controls the valve that covers the water inlet in the boiler.

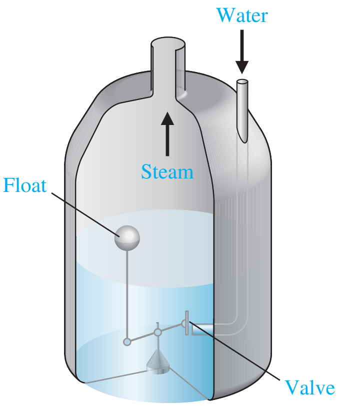

FIGURE 1.8 Water-level float regulator.

The next century was characterized by the development of automatic control systems through intuition and invention. Efforts to increase the accuracy of the control system led to slower attenuation of the transient oscillations and even to unstable systems. It then became imperative to develop a theory of automatic control. In 1868, J. C. Maxwell formulated a mathematical theory related to control theory using a differential equation model of a governor [5]. Maxwell's study was concerned with the effect various system parameters had on the system performance. During the same period, I. A. Vyshnegradskii formulated a mathematical theory of regulators [6].

Prior to World War II, control theory and practice developed differently in the United States and western Europe than in Russia and eastern Europe. The main impetus for the use of feedback in the United States was the development of the telephone system and electronic feedback amplifiers by Bode, Nyquist, and Black at Bell Telephone Laboratories [7–10, 12].

Harold S. Black graduated from Worcester Polytechnic Institute in 1921 and joined Bell Laboratories of American Telegraph and Telephone (AT&T). In 1921, the major task confronting Bell Laboratories was the improvement of the telephone system and the design of improved signal amplifiers. Black was assigned the task of linearizing, stabilizing, and improving the amplifiers that were used in tandem to carry conversations over distances of several thousand miles.

Black reports [8]:

> Then came the morning of Tuesday, August 2, 1927, when the concept of the negative feedback amplifier came to me in a flash while I was crossing the Hudson River on the Lackawanna Ferry, on my way to work. For more than 50 years I have pondered how and why the idea came, and I can't say any more today than I could that morning. All I know is that after several years of hard work on the problem, I suddenly realized that if I fed the amplifier output back to the input, in reverse phase, and kept the device from oscillating (singing, as we called it then), I would have exactly what I wanted: a means of canceling out the distortion in the output. I opened my morning newspaper and on a page of *The New York Times* I sketched a simple canonical diagram of a negative feedback amplifier plus the equations for the amplification with feedback. I signed the sketch, and 20 minutes later, when I reached the laboratory at 463 West Street, it was witnessed, understood, and signed by the late Earl C. Blessing.
>
> I envisioned this circuit as leading to extremely linear amplifiers (40 to 50 dB of negative feedback), but an important question is: How did I know I could avoid self-oscillations over very wide frequency bands when many people doubted such circuits would be stable? My confidence stemmed from work that I had done two years earlier on certain novel oscillator circuits and three years earlier in designing the terminal circuits, including the filters, and developing the mathematics for a carrier telephone system for short toll circuits.

The frequency domain was used primarily to describe the operation of the feedback amplifiers in terms of bandwidth and other frequency variables. In contrast, the eminent mathematicians and applied mechanicians in the former Soviet Union inspired and dominated the field of control theory. Therefore, the Russian theory tended to utilize a time-domain formulation using differential equations.

The control of an industrial process (manufacturing, production, and so on) by automatic rather than manual means is often called **automation**. Automation is prevalent in the chemical, electric power, paper, automobile, and steel industries, among others. The concept of automation is central to our industrial society. Automatic machines are used to increase the production of a plant per worker in order to offset rising wages and inflationary costs. Thus industries are concerned with the productivity per worker of their plants. **Productivity** is defined as the ratio of physical output to physical input [26]. In this case, we are referring to labor productivity, which is real output per hour of work.

A large impetus to the theory and practice of automatic control occurred during World War II when it became necessary to design and construct automatic airplane piloting, gun-positioning systems, radar antenna control systems, and other military systems based on the feedback control approach. The complexity and expected performance of these military systems necessitated an extension of the available control techniques and fostered interest in control systems and the development of new insights and methods. Prior to 1940, for most cases, the design of control systems was an art involving a trial-and-error approach. During the 1940s, mathematical and analytical methods increased in number and utility, and control engineering became an engineering discipline in its own right [10–12].

Another example of the discovery of an engineering solution to a control system problem was the creation of a gun director by David B. Parkinson of Bell Telephone Laboratories. In the spring of 1940, Parkinson was a 29-year-old engineer intent on improving the automatic level recorder, an instrument that used strip-chart paper to plot the record of a voltage. A critical component was a small potentiometer used to control the pen of the recorder through an actuator.

Parkinson had a dream about an antiaircraft gun that was successfully felling airplanes. Parkinson described the situation [13]:

> After three or four shots one of the men in the crew smiled at me and beckoned me to come closer to the gun. When I drew near he pointed to the exposed end of the left trunnion. Mounted there was the control potentiometer of my level recorder!

The next morning Parkinson realized the significance of his dream:

> If my potentiometer could control the pen on the recorder, something similar could, with suitable engineering, control an antiaircraft gun.

After considerable effort, an engineering model was delivered for testing to the U.S. Army on December 1, 1941. Production models were available by early 1943, and eventually 3000 gun controllers were delivered. Input to the controller was provided by radar, and the gun was aimed by taking the data of the airplane's present position and calculating the target's future position.

Frequency-domain techniques continued to dominate the field of control following World War II with the increased use of the Laplace transform and the complex frequency plane. During the 1950s, the emphasis in control engineering theory was on the development and use of the s-plane methods and, particularly, the root locus approach. Furthermore, during the 1980s, the use of digital computers for control components became routine. The technology of these new control elements to perform accurate and rapid calculations was formerly unavailable to control engineers. These computers are now employed especially for process control systems in which many variables are measured and controlled simultaneously by the computer.

With the advent of Sputnik and the space age, another new impetus was imparted to control engineering. It became necessary to design complex, highly accurate control systems for missiles and space probes. Furthermore, the necessity to minimize the weight of satellites and to control them very accurately has spawned the important field of optimal control. Due to these requirements, the time-domain methods developed by Liapunov, Minorsky, and others have been met with great interest in the last two decades. Recent theories of optimal control developed by L. S. Pontryagin in the former Soviet Union and R. Bellman in the United States, as well as recent studies of robust systems, have contributed to the interest in time-domain methods. It now is clear that control engineering must consider both the time-domain and the frequency-domain approaches simultaneously in the analysis and design of control systems.

A notable advance with worldwide impact is the U.S. space-based radionavigation system known as the Global Positioning System or GPS [82–85]. In the distant past, various strategies and sensors were developed to keep explorers on the oceans from getting lost, including following coastlines, using compasses to point north, and sextants to measure the angles of stars, the moon, and the sun above the horizon. The early explorers were able to estimate latitude accurately, but not longitude. It was not until the 1700s with the development of the chronometer that, when used with the sextant, the longitude could be estimated. Radio-based navigation systems began to appear in the early twentieth century and were used in World War II. With the advent of Sputnik and the space age, it became known that radio signals from satellites could be used to navigate on the ground by observing the Doppler shift of the received radio signals. Research and development culminated in the 1990s with 24 navigation satellites (known as the GPS) that solved the fundamental problem that explorers faced for centuries by providing a dependable mechanism to pinpoint the current location. Freely available on a continuous worldwide basis, GPS provides very reliable location and time information anytime, day or night, anywhere in the world. Using GPS as a sensor to provide position (and velocity) information is a mainstay of active control systems for transportation systems in the air, on the ground, and on the oceans. The GPS assists relief and emergency workers to save lives, and helps us with our everyday activities including the control of power grids, banking, farming, surveying, and many other tasks.

The evolution of the **Internet of Things (IoT)** is likely to have a transformational impact on the field of control engineering. The idea of the IoT, first proposed by Kevin Ashton in 1999, is the network of physical objects embedded with electronics, software, sensors, and connectivity—all elements of control engineering [14]. Each of the "things" on the network has an embedded computer with connectivity to the Internet. The ability to control connected devices is of great interest to control engineers, but there remains much work to be done, especially in establishing standards [24]. Figure 1.9 presents a technology roadmap that illustrates that in the near future control engineering is likely to play a role in creating active control applications for connected devices (adopted from [27]).

A selected history of control system development is summarized in Table 1.1.