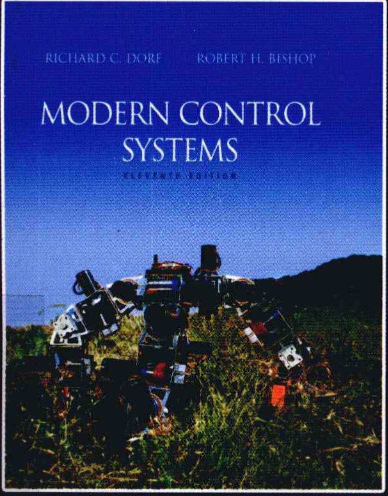
国外计算机科学教材系列

PEARSON

现代控制系统

（第十一版）

Modern Control Systems, Eleventh Edition



英文版

[美] Richard C Dorf
Robert H. Bishop 著

電子工業出版社
PUBLISHING HOUSE OF ELECTRONICS INDUSTRY

http://www.phei.com.cn

权威作者
经典力作

国外计算机科学教材系列

现代控制系统

（第十一版）

（英文版）

Modern Control Systems

Eleventh Edition

[美] Richard C. Dorf
Robert H. Bishop 著

電子工業出版社
Publishing House of Electronics Industry
北京 · BEIJING

内容简介

控制系统原理及相近课程是高等学校工科学生的核心课程之一。本书一直是该类课程畅销全球的教材范本，至今已出版至第十一版。主要内容包括控制系统导论、系统数学模型、状态空间模型、反馈控制系统的特性、反馈控制系统的性能、反馈系统的稳定性、根轨迹法、频率响应方法、频域稳定性、反馈控制系统设计、状态变量反馈系统设计、鲁棒控制系统和数字控制系统等。本书的例子和习题大多取材于现代科技领域中的实际问题，新颖而恰当。学习和解决这些问题，可以使学生的创造性精神得到潜移默化的提升。

本书可作为高等学校工科（自动化、航空航天、电力、机械、化工等）本科高年级学生和研究生教材，也可供从事相关工作的人员作为参考用书使用。

版权贸易合同登记号　图字：01-2009-1391

图书在版编目（CIP）数据

现代控制系统 =Modern Control Systems: 第 11 版：英文 /（美）多尔夫（Dorf, R. C.），（美）毕晓普（Bishop, R. H.）著. -北京：电子工业出版社，2009.6
（国外计算机科学教材系列）
ISBN 978-7-121-08841-4

Ⅰ. 现…　Ⅱ. ①多…　②毕…　Ⅲ. 控制系统 - 高等学校 - 教材 - 英文　Ⅳ. TP271

中国版本图书馆 CIP 数据核字（2009）第 075045 号

责任编辑：马　岚
印　　刷：北京市天竺颖华印刷厂
装　　订：三河市鑫金马印装有限公司
出版发行：电子工业出版社
　　　　　北京市海淀区万寿路 173 信箱　邮编：100036
开　　本：787 × 980　1/16　　印张：65.25　　字数：1462 千字
印　　次：2009 年 6 月第 1 次印刷
定　　价：98.00 元

凡所购买电子工业出版社的图书有缺损问题，请向购买书店调换；若书店售缺，请与本社发行部联系。联系及邮购电话：（010）88254888。

质量投诉请发邮件至 zlts@phei.com.cn，盗版侵权举报请发邮件至 dbqq@phei.com.cn。

服务热线：（010）88258888。

Preface

MODERN CONTROL SYSTEMS—THE BOOK

The Mars Exploration Rover (MER-A), also known as *Spirit,* was launched on a Delta II rocket, in June 2003 to Mars, the Red Planet. *Spirit* entered the Martian atmosphere seven months later in January, 2004. When the spacecraft entered the Martian atmosphere it was traveling 19,300 kilometers per hour. For about four minutes in the upper atmosphere, the spacecraft aeroshell decelerated the vehicle to a velocity of 1,600 kilometers per hour. Then a parachute was deployed to slow the spacecraft to about 300 kilometers per hour. At an altitude of about 100 meters, retrorockets slowed the descent and airbags were inflated to cushion the shock of landing. The *Spirit* struck the Martian ground at around 50 km/hr and bounced and rolled until it stopped near the target point in the Gusev Crater. The target landing site was chosen because it looks like a crater lakebed. The *Spirit* mobile rover has reached interesting places in the Gusev Crater to perform in-situ tests to help scientists answer many of the lingering questions about the history of our neighbor planet. In fact, *Spirit* discovered evidence of an ancient volcanic explosion near the landing site in Gusev Crater. The successful entry, descent, and landing of *Spirit* is an astonishing illustration of the power of control systems. Given the large distances to Mars, it is not possible for a spacecraft to fly through the atmosphere while under ground control—the entry, descent, and landing must be controlled autonomously on-board the spacecraft. Designing systems capable of performing planetary entry is one of the great challenges facing control system engineers.

The precursor NASA Mars mission, known as the Mars Pathfinder, also journeyed to the Red Planet and landed on July 4, 1997. The Pathfinder mission, one of the first of the NASA Discovery-class missions, was the first mission to land on Mars since the successful Viking spacecraft in the 1970s. Pathfinder deployed the first-ever autonomous rover vehicle, known as the *Sojourner,* to explore the landing site area. The mobile *Sojourner* had a mass of 10.5 kilograms and traveled a total of 100 meters (never straying more than 12 meters or so from the lander) in its 30-day mission. By comparison, the *Spirit* rover has a mass of 180 kilograms and is designed to roam about 40 meters per day. *Spirit* has spent four years exploring Mars and has driven over 7 kilometers. The fast pace of development of more capable planetary rovers is evident. Plans for the Mars Science Laboratory planetary rover (scheduled for launch in 2009) call for a 1000-kilogram rover with a mission duration of 500 days and the capability to traverse 30 kilometers over the mission lifetime.

Control engineers play a critical role in the success of the planetary exploration program. The role of autonomous vehicle spacecraft control systems will continue to increase as flight computer hardware and operating systems improve. Pathfinder used a commercially produced, multitasking computer operating system hosted in a 32-bit radiation-hardened workstation with 1-gigabyte storage, programmable in C.

This was quite an advancement over the Apollo computers, which had a fixed (read-only) memory of 36,864 words (one word was 16 bits) together with an erasable memory of 2,048 words. The Apollo "programming language" was a pseudocode notation encoded and stored as a list of data words "interpreted" and translated into a sequence of subroutine links.[1] The MER computer in the Spirit rover utilizes a 32-bit Rad 6000 microprocessor operating at a speed of 20 million instructions per second. This is a radiation-hardened version of the PowerPC chip used in many Macintosh computers. The on-board memory includes 128 megabytes of random access memory, 256 megabytes of flash memory, and smaller amounts of other nonvolatile memory to protect against power-off cycles so that data will not be unintentionally erased. The total memory and power of the MER computers is approximately the equivalent memory of a typical powerful laptop. As with all space mission computers, the *Spirit* computer contains special memory to tolerate the extreme radiation environment from space. Interesting real-world problems, such as planetary mobile rovers like *Spirit* and *Sojourner*, are used as illustrative examples throughout the book. For example, a mobile rover design problem is discussed in the Design Example in Section 4.8.

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.

---

[1] For further reading on the Apollo guidance, navigation, and control system, see R. H. Battin, *An Introduction to the Mathematics and Methods of Astrodynamics,* AIAA Education Series, J. S. Pzemieniecki/Series Editor-in-Chief, 1987.

THE AUDIENCE

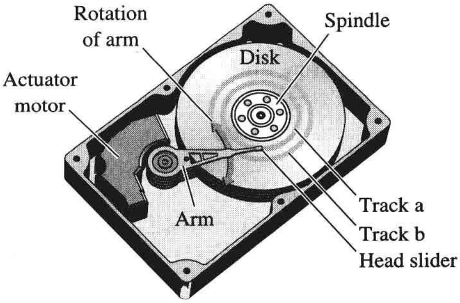
This text is designed for an introductory undergraduate course in control systems for engineering students. There is very little demarcation between aerospace, chemical, electrical, industrial, and mechanical engineering in control system practice; therefore, this text is written without any conscious 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. For example, many electrical and mechanical engineers find themselves in the aerospace industry working alongside aerospace engineers. We hope this introduction to control engineering will give students a broader understanding of control system design and analysis.

In its first ten editions, *Modern Control Systems* has been used in senior-level courses for engineering students at more than 400 colleges and universities. It also has been used in courses for engineering graduate students with no previous background in control engineering.

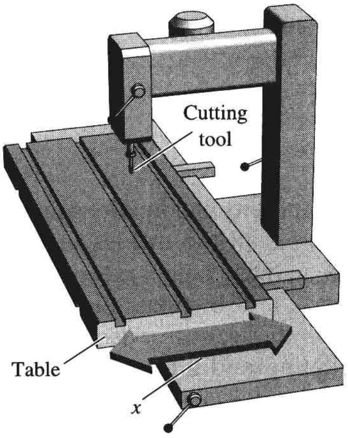
THE ELEVENTH EDITION

A companion website is available to students and faculty using the eleventh edition. The website contains practice exercises, all the m-files in the book, Laplace and z-transform tables, written materials on matrix algebra, complex numbers, and symbols, units, and conversion factors. An icon will appear in the book margin whenever there is additional related material on the website. Also, since the website provides a mechanism for continuously updating and adding control-related materials of interest to students and professors, it is advisable to visit the website regularly during the semester or quarter when taking the course. The MCS website address is http://www.prenhall.com/dorf.

With the eleventh edition, we continue to evolve 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* (identified by an arrow icon in the text), 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* (identified by a triple arrow icon in the text) 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. The end-of-chapter computer problem set is identified by the graphical icon in the text. Also, many of the solutions to various components of the *Sequential Design Example* utilize m-files with corresponding scripts included in the figures.

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. Advances in robust control theory are introduced in Chapter 12. The implementation of digital computer control systems is discussed in Chapter 13. Each chapter (but the first) introduces the student to the notion of computer-aided design and analysis. The book concludes with an extensive references section, divided by chapter, to guide the student to further sources of information on control engineering.

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 The Root Locus Method, Chapter 7 (see page 407) includes 27 exercises, 39 problems, 13 advanced problems, 13 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 800 problems. Also, the MCS website contains practice exercises that are instantly graded, so they provide quick feedback for students. 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. A complete instructor manual, available for all adopters of the text for course use, contains complete solutions to all end-of-chapter problems.

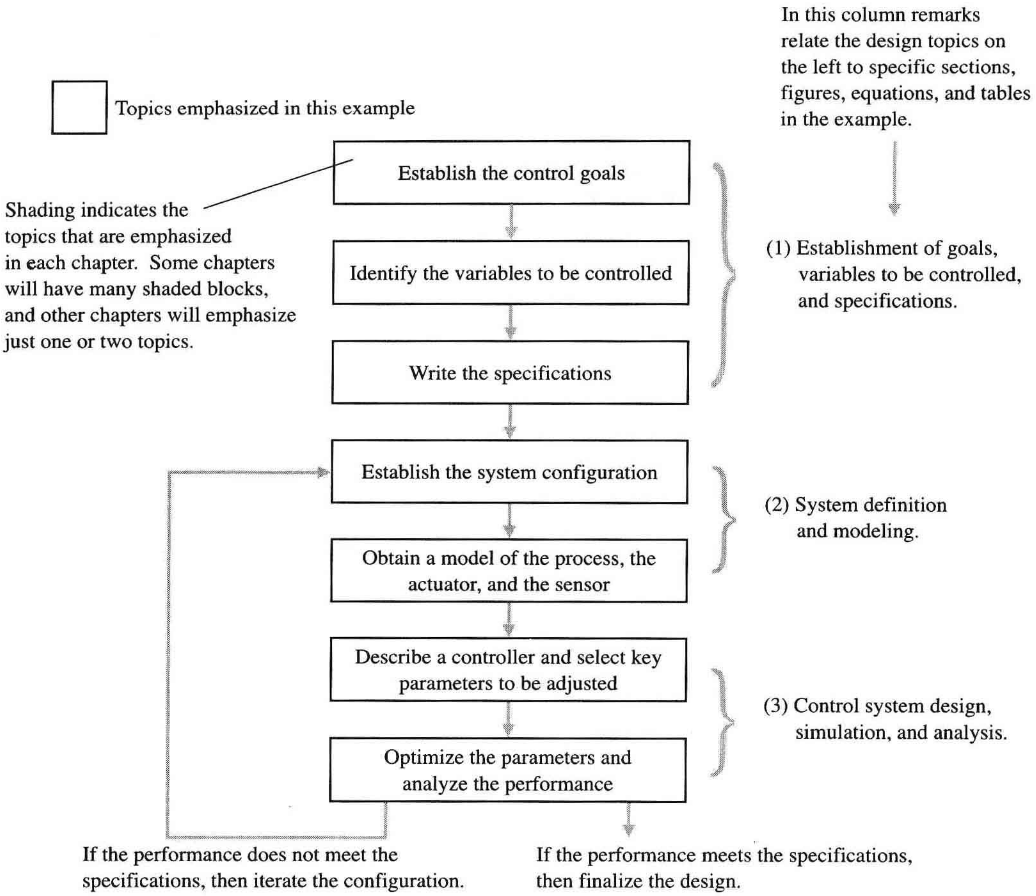
A set of m-files, the *Modern Control Systems Toolbox,* has been developed by the authors to supplement the text. The m-files contain the scripts from each computer-based example in the text. You may retrieve the m-files from Prentice Hall at http://www.prenhall.com/dorf.

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 which 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 the following examples:

- ☐ insulin delivery control system (Section 1.8, page 27)
- ☐ fluid flow modeling (Section 2.8, page 83)
- ☐ space station orientation modeling (Section 3.8, page 176)
- ☐ blood pressure control during anesthesia (Section 4.8, page 237)
- ☐ attitude control of an airplane (Section 5.9, page 319)
- ☐ robot-controlled motorcycle (Section 6.5, page 375)
- ☐ automobile velocity control (Section 7.7, page 452)
- ☐ control of one leg of a six-legged robot (Section 8.6, page 526)
- ☐ hot ingot robot control (Section 9.8, page 610)
- ☐ milling machine control system (Section 10.12, page 714)
- ☐ diesel electric locomotive control (Section 11.9, page 798)
- ☐ digital audio tape controller (Section 12.8, page 861)
- ☐ fly-by-wire aircraft control surface (Section 13.10, page 928)



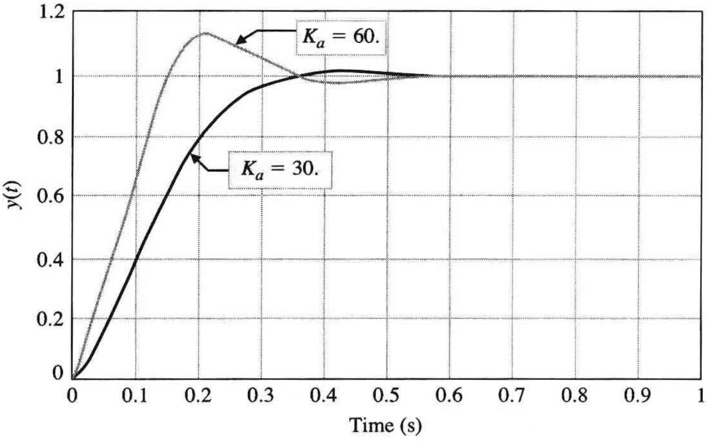
Each chapter includes a section to assist students in utilizing computer-aided design and analysis concepts and rework many of the design examples. In Chapter 5, the Sequential Design Example: Disk Drive Read System is analyzed using computer-based methods. An m-file script that can be used to analyze the design is presented in Figure 5.47, p. 335. In general, 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.

```
Ka=30;
t=[0:0.01:1];
nc=[Ka*5];dc=[1]; sysc=tf(nc,dc);
ng=[1];dg=[1 20 0]; sysg=tf(ng,dg);
sys1=series(sysc,sysg);
sys=feedback(sys1, [1]);
y=step(sys,t);
plot(t,y), grid
xlabel('Time (s)')
ylabel('y(t)')
```

Select K_a.

Compute the closed-loop transfer function.

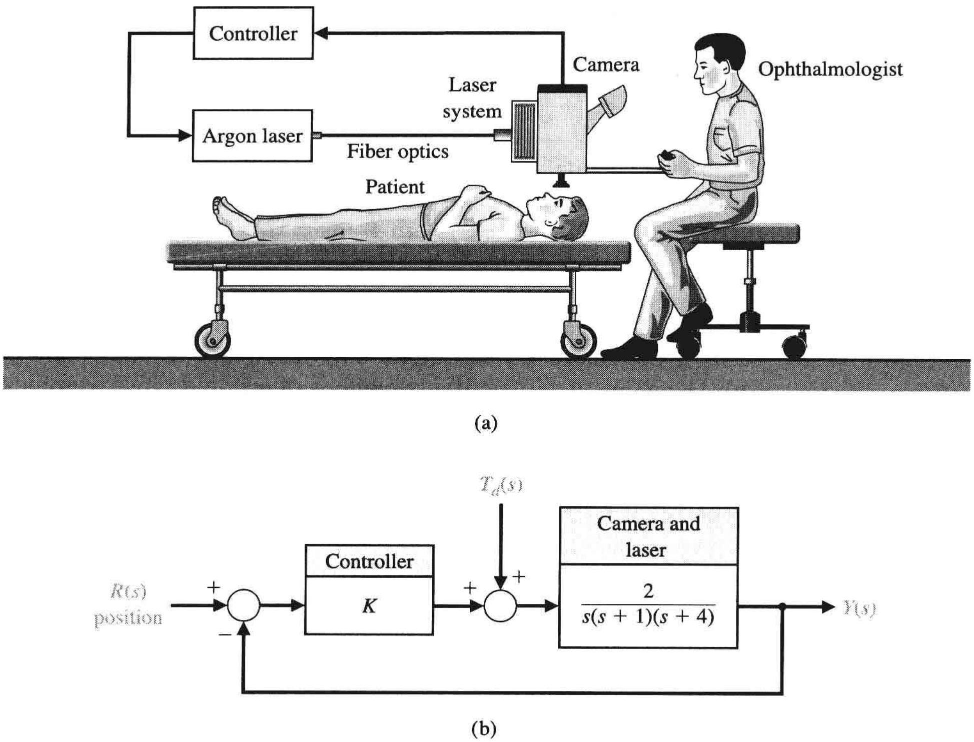
(a)



(b)

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, 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. Design Problem 4.4, page 217, asks the student to determine the value of K of the controller so that the response, denoted by $Y(s)$, to a step change in the position, denoted by $R(s)$, is satisfactory and the effect of the disturbance, denoted by $T_d(s)$, is minimized. The associated Figure DP4.4, p. 272, assists the student with (a) visualizing the problem and (b) taking the next step to develop the transfer function model and to complete the design.



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.

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 (including mechanical, electrical, and fluid) are considered.

Chapter 3 State Variable Models. Mathematical models of systems in state variable form are developed in Chapter 3. Using matrix methods, 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.

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.

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.

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.

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.

Appendixes. The appendixes are as follows:

A MATLAB Basics
B MathScript Basics

ACKNOWLEDGMENTS

We wish to express our sincere appreciation to the following individuals who have assisted us with the development of this eleventh 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; Jure Medanic, University of Illinois at Urbana-Champaign; Eduardo A. Misawa, Oklahoma State University; Medhat M. Morcos, Kansas State University; Mark Nagurka, Marquette University; Carla Schwartz, The MathWorks, Inc.; D. Subbaram Naidu, Idaho State University; Ron Perez, University of Wisconsin-Milwaukee; 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.

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 interesting comments of other users.

Keep in touch!

Richard C. Dorf dorf@ece.ucdavis.edu
Robert H. Bishop rhbishop@mail.utexas.edu

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 Chairman of the Department of Aerospace Engineering and Engineering Mechanics at The University of Texas at Austin. He holds the Joe J. King Professorship and in 2002 was inducted into the UT Academy of Distinguished Teachers. A talented educator, Professor Bishop has been recognized for his contributions in the classroom with the coveted Lockheed Martin Tactical Aircraft Systems Award for Excellence in Engineering Teaching. He received the John Leland Atwood Award from the American Society of Engineering Educators and the American Institute of Aeronautics and Astronautics, which is periodically given to "a leader who has made lasting and significant contributions to aerospace engineering education." Professor Bishop is a Fellow of AIAA and is active in the IEEE and ASEE. He is a distinguished researcher with an interest in guidance, navigation, and control of aerospace vehicles.

Design Examples and Design Problems (DP)

CHAPTER 1 PAGE

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER 7

CHAPTER 8

CHAPTER 9

CHAPTER 10

CHAPTER 11

CHAPTER 12

CHAPTER 13