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国外高校电子信息类优秀教材

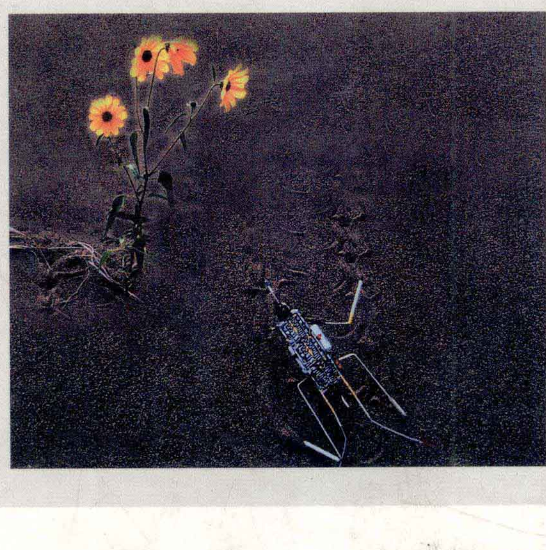
现代控制系统

（第九版）

Modern Control Systems

(Ninth Edition)

（英文影印版）



Richard C. Dorf　Robert H. Bishop 著

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内 容 简 介

本书为国外高校电子信息类优秀教材(英文影印版)之一。

本书主要内容有控制系统的数学模型、反馈控制系统及其设计、根轨迹法、频率响应法、稳定控制系统和数字控制系统等。本书内容别有新意,反映了控制系统的最新内容。

本书适用于高等院校电气工程、机电工程及相关专业本科生,也可供一般工程技术人员参考。

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丛书编委会

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

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 text books and handbooks, including the best selling *Engineering Handbook* and the Second Edition of the *Electrical Engineering Handbook.* Professor Dorf is a Fellow of the IEEE and is active in the fields of control system design and robotics. Dr. Dorf holds a patent for the PIDA controller.

Robert H. Bishop holds the Myron L. Begeman Fellowship in Engineering in the Department of Aerospace Engineering and Engineering Mechanics at The University of Texas at Austin. 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. An active member of AIAA, IEEE, and ASEE, he recently received the John Leland Atwood Award from the American Society of Engineering Educators and the American Institute of Aeronautics and Astronautics which is given periodically to "a leader who has made lasting and significant contributions to aerospace engineering education." Dr. Bishop is a distinguished researcher with an interest in guidance, navigation, and control of aerospace vehicles.

ABOUT THE COVER

"Unibug 1.0" walking past desert flowers at Grand Sand Dunes National Monument in Colorado. This Image is from the upcoming Photography book entitled "Robo sapiens" by Peter Menzel and Faith D'Aluisio. Material World Books. M.I.T. Press, Fall, 2000. Photography provided by Peter Menzel and Mark Tilden's robots—Analog Nervous Net.

Preface

MODERN CONTROL SYSTEMS—THE BOOK

The Mars Pathfinder spacecraft was sent aloft aboard a Delta II expendable launch vehicle on December 4, 1996 to begin a seven-month journey to the Red Planet. 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 over two decades ago. After traveling over 497,418,000 km, the spacecraft impacted the Martian surface on July 4, 1997 with a velocity of about 18 m/s. Upon impact the spacecraft bounced up approximately 15 meters, then continued to bounce another 15 times and rolled to a stop about 1 km from the initial impact point. The landing site is known as the *Sagan Memorial Station* and is located in the Ares Vallis region at 19.33 N, 33.55 W. 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 was designed to roam in a 300-m^2 area for around 30 days. The 0.25-m^2 solar array provided 16 Wh and the primary battery provided about 150 Wh. The steering control of this vehicle had to be accurate and had to limit the power consumption. 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. In fact, 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 is quite an advancement over the Apollo computers with 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] Interesting real-world problems, such as planetary mobile rovers like *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, one 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, one might take an ad hoc approach relying only on intuition and hands-on experience when designing feedback

[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.

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 recreate 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.

THE AUDIENCE

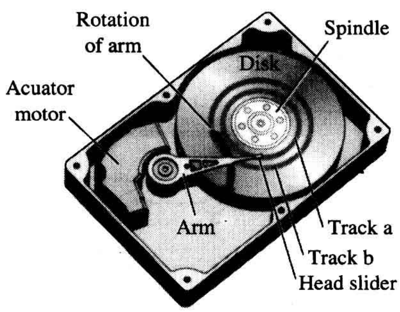
This text is designed for an introductory undergraduate course in control systems for engineering students. There is very little demarcation between aerospace, chemical, electrical, industrial, and mechanical engineering in control system practice; therefore this text is written without any conscious 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 eight 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.

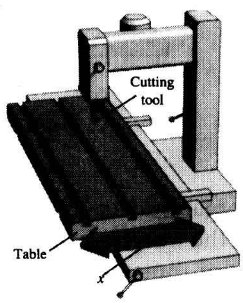
THE NINTH EDITION

A companion website has been developed for students and faculty using the ninth edition. The website contains practice exercises and exam problems, all the MATLAB m-files and Simulink simulations 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 ninth 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 seqentially 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.



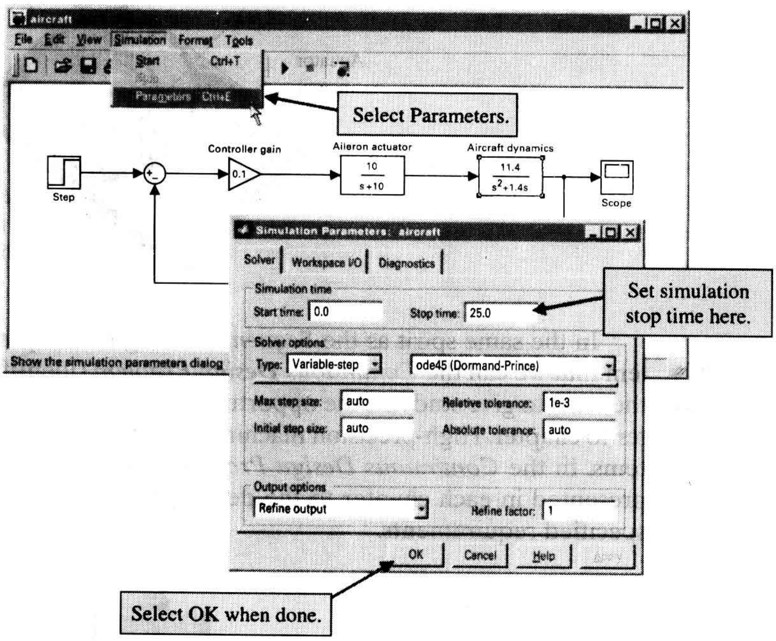
In the same spirit as the *Sequential Design Example,* we present a design problem that we call the *Continuous Design Problem* (identified by a triple arrow icon in the text) to give students the opportunity to build upon a design problem from chapter to chapter. High-precision machinery places stringent 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 MATLAB* end-of-chapter problem set are identified by the graphical icon in the text. Also, many of the solutions to various components of the *Sequential Design Example* utilize MATLAB with corresponding scripts included in the figures.

In the ninth edition, we introduce the use of Simulink as an efficient way for MATLAB users to model, simulate, and analyze feedback control systems. Since Simulink is an interactive tool utilizing graphical interfaces effectively, we believe that the best way to learn about it is to jump right in and use it. Appendix B is devoted to the basics of Simulink where the student can walk through a sequence of steps to construct and simulate a simple system. We attempt to provide basic information about Simulink that is as loosely tied to specific releases of the software as possible. At the time of this ninth edition, the latest version is Simulink 3.0. As different versions of Simulink are released, previous introductions to Simulink Basics will be posted on the *MCS* website—check there if you are having compatibility problems with the Simulink models in this book.

Simulink examples are presented in Chapters 5 and 11. In Chapter 5, aircraft roll control is investigated using Simulink. In Chapter 11, a Simulink simulation is developed to study a system in state variable form.



PEDAGOGY

The book is organized around the concepts of control system theory as they have been developed in the frequency and time domains. A real attempt has been made to make the selection of topics, as well as the systems discussed in the examples and prob-

* MATLAB is a registered trademark of The MathWorks, Inc.

lems, 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.

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 uses a MATLAB section to introduce 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
- ❑ MATLAB Problems

For example, the problem set for State Variable Models, Chapter 3 (see page 159) includes 19 exercises, 36 problems, 6 advanced problems, 5 design problems, and 7 MATLAB problems. The exercises permit the students to utilize readily 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. Introduced in the seventh edition to the problem set, the advanced problems represent problems of increasing complexity. The design problems emphasize the design task; the MATLAB 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 providing 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 MATLAB 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 MATLAB and Simulink example in the text. You may retrieve the M-files from Prentice Hall at www.prenhall.com/dorf.

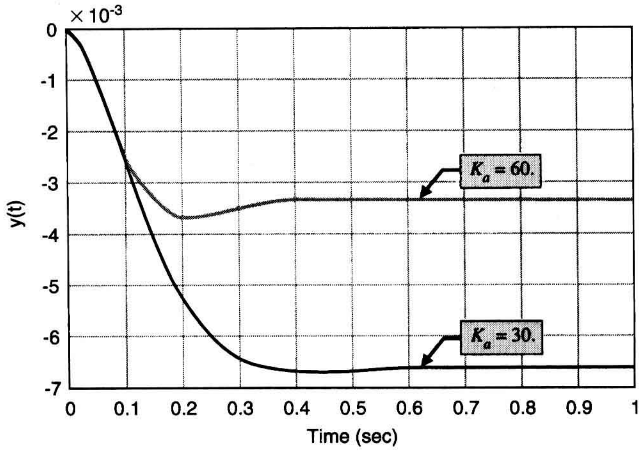
Design Emphasis Without Compromising Basic Principles. The all-important topic of design of real-world, complex control systems is a major theme throughout the text. Emphasis on design for real-world applications addresses interest in design by ABET and industry. Each chapter contains at least one design example, including the following:

- ❑ insulin delivery control (Sec. 1.11, page 22)
- ❑ low-pass filter (Sec. 2.9, page 72)
- ❑ printer belt drive (Sec. 3.9, page 147)
- ❑ Mars rover vehicle (Sec. 4.8, page 194)
- ❑ Hubble Space Telescope pointing control (Sec. 5.11, page 259)
- ❑ tracked vehicle turning control (Sec. 6.5, page 307)
- ❑ laser manipulator control system (Sec. 7.8, page 368)
- ❑ engraving machine control system (Sec. 8.7, page 435)
- ❑ remotely controlled reconnaissance vehicle (Sec. 9.8, page 505)
- ❑ *x-y* plotter (Sec. 10.13, page 595)
- ❑ automatic test system (Sec. 11.9, page 655)
- ❑ ultra-precision diamond turning machine (Sec. 12.12, page 710)
- ❑ worktable motion control system (Sec. 13.9, page 762)

The MATLAB sections 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 MATLAB. A MATLAB script that can be used to analyze the design is presented in Figure 5.53, p. 274. 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;                                   <-- Select Ka.
t=[0:0.01:1];
nc=[Ka*5];dc=[1]; sysc=tf(nc,dc);
ng=[1];dg=[1 20 0]; sysg=tf(ng,dg);
sys=feedback(sysg,sysc);
sys=-sys;                                <-- Disturbance enters summer with a negative sign.
step(sys,t);
xlabel('Time (sec)'), ylabel('y(t)')
```

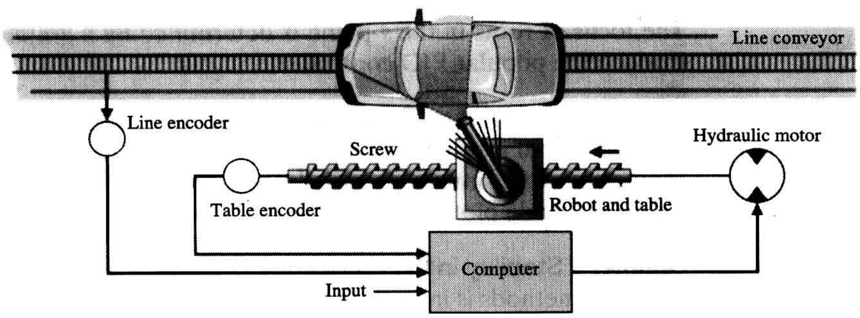
(a)



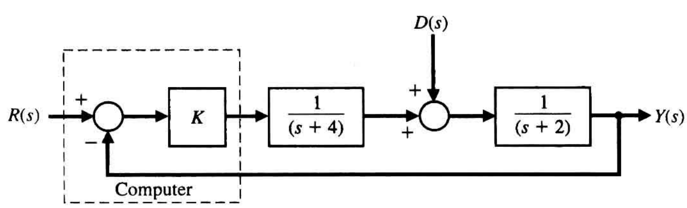
(b)

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 and 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. Problem 12.4, page 726, asks the student to determine the value of Ka to meet specified design goals. The associated Figure 12.4, p. 726, assists the student with (a) visualizing the problem, and (b) taking the next step to develop the transfer function model:



(a)



(b)

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 sinusoida 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 Nyquis 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. 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:

A MATLAB Basics

B Simulink Basics

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We wish to express our sincere appreciation to the following individuals who have assisted us with the development of this ninth 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 and the staff at Prentice Hall would like to establish a line of communication with the users of *Modern Control Systems.* We encourage all readers to send Prentice Hall your e-mail address and pass along 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!

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