Control Systems Engineering
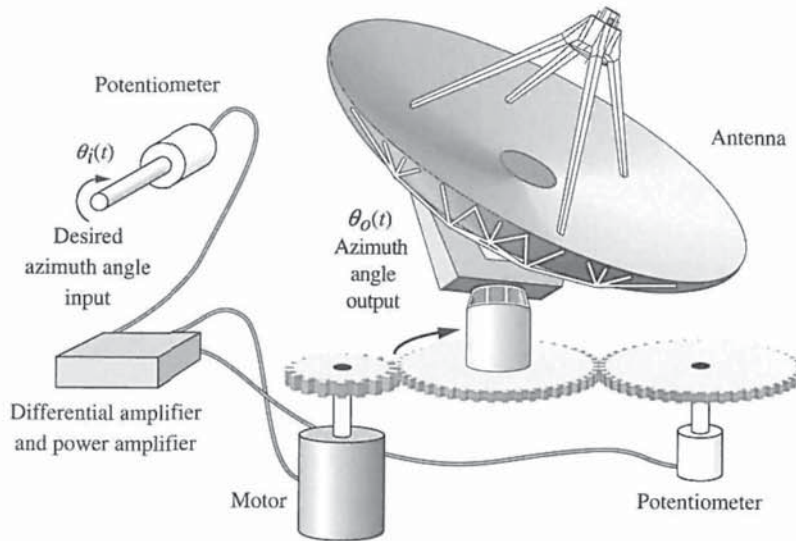
Sixth edition

NORMAN S. NISE

NORMAN S. NISE

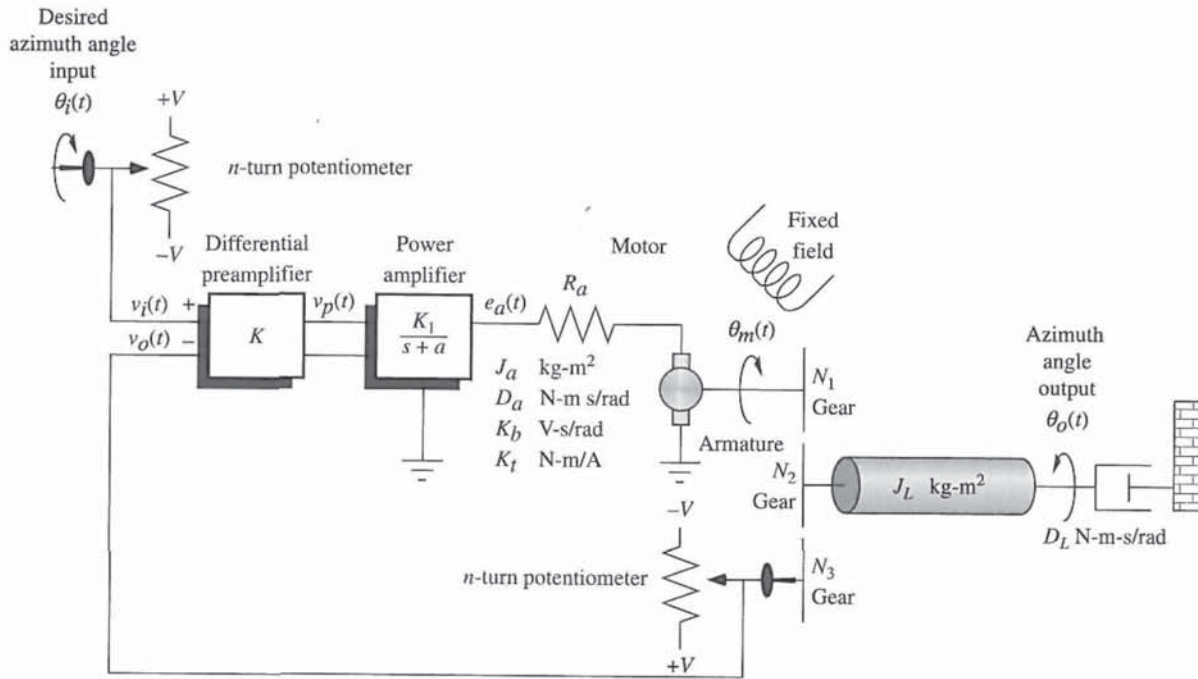# CONTROL SYSTEMS ENGINEERING

SIXTH EDITION

Antenna Azimuth Position Control System
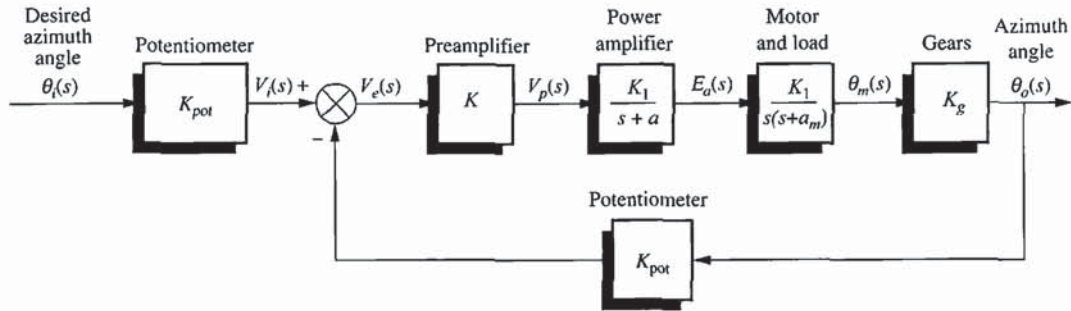
Layout

Schematic

Block Diagram

Schematic Parameters

Parameter	Configuration 1	Configuration 2	Configuration 3
V	10	10	10
n	10	1	1
K	—	—	—
K_1	100	150	100
a	100	150	100
R_a	8	5	5
J_a	0.02	0.05	0.05
D_a	0.01	0.01	0.01
K_b	0.5	1	1
K_t	0.5	1	1
N_1	25	50	50
N_2	250	250	250
N_3	250	250	250
J_L	1	5	5
D_L	1	3	3

Block Diagram Parameters

Parameter	Configuration 1	Configuration 2	Configuration 3
K_{pot}	0.318		
K	—		
K_1	100		
a	100		
K_m	2.083		
a_m	1.71		
K_g	0.1		

Note: reader may fill in Configuration 2 and Configuration 3 columns after completing the antenna control Case Study challenge problems in Chapters 2 and 10, respectively.

CONTROL SYSTEMS ENGINEERING
Sixth Edition

Norman S. Nise

California State Polytechnic University, Pomona

WILEY

John Wiley & Sons, Inc.

To my wife, Ellen; sons, Benjamin and Alan; and daughter, Sharon, and their families.

Contents

Online location is www.wiley.com/college/nise

Preface

This book introduces students to the theory and practice of control systems engineering. The text emphasizes the practical application of the subject to the analysis and design of feedback systems.

The study of control systems engineering is essential for students pursuing degrees in electrical, mechanical, aerospace, biomedical, or chemical engineering. Control systems are found in a broad range of applications within these disciplines, from aircraft and spacecraft to robots and process control systems.

Control Systems Engineering is suitable for upper-division college and university engineering students and for those who wish to master the subject matter through self-study. The student using this text should have completed typical lower-division courses in physics and mathematics through differential equations. Other required background material, including Laplace transforms and linear algebra, is incorporated in the text, either within chapter discussions or separately in the appendixes or on the book's Companion Web site. This review material can be omitted without loss of continuity if the student does not require it.

❰ Key Features

The key features of this sixth edition are:

- Standardized chapter organization
- Qualitative and quantitative explanations
- **Examples, Skill-Assessment Exercises,** and **Case Studies** throughout the text
- WileyPLUS content management system for students and professors
- **Cyber Exploration Laboratory and Virtual Experiments**
- Abundant illustrations
- Numerous end-of-chapter problems
- Emphasis on design
- Flexible coverage
- Emphasis on computer-aided analysis and design including MATLAB[1] and LabVIEW[2]

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[1] MATLAB is a registered trademark of The MathWorks, Inc.

[2] LabVIEW is a registered trademark of National Instruments Corporation.

- Icons identifying major topics

Let us look at each feature in more detail.

Standardized Chapter Organization

Each chapter begins with a list of chapter learning outcomes, followed by a list of case study learning outcomes that relate to specific student performance in solving a practical case study problem, such as an antenna azimuth position control system.

Topics are then divided into clearly numbered and labeled sections containing explanations, examples, and, where appropriate, skill-assessment exercises with answers. These numbered sections are followed by one or more case studies, as will be outlined in a few paragraphs. Each chapter ends with a brief summary, several review questions requiring short answers, a set of homework problems, and experiments.

Qualitative and Quantitative Explanations

Explanations are clear and complete and, where appropriate, include a brief review of required background material. Topics build upon and support one another in a logical fashion. Groundwork for new concepts and terminology is carefully laid to avoid overwhelming the student and to facilitate self-study.

Although quantitative solutions are obviously important, a qualitative or intuitive understanding of problems and methods of solution is vital to producing the insight required to develop sound designs. Therefore, whenever possible, new concepts are discussed from a qualitative perspective before quantitative analysis and design are addressed. For example, in Chapter 8 the student can simply look at the root locus and describe qualitatively the changes in transient response that will occur as a system parameter, such as gain, is varied. This ability is developed with the help of a few simple equations from Chapter 4.

Examples, Skill-Assessment Exercises, and Case Studies

Explanations are clearly illustrated by means of numerous numbered and labeled **Examples** throughout the text. Where appropriate, sections conclude with **Skill-Assessment Exercises**. These are computation drills, most with answers that test comprehension and provide immediate feedback. Complete solutions can be found at www.wiley.com/college/nise.

Broader examples in the form of **Case Studies** can be found after the last numbered section of every chapter, with the exception of Chapter 1. These case studies arc practical application problems that demonstrate the concepts introduced in the chapter. Each case study concludes with a "Challenge" problem that students may work in order to test their understanding of the material.

One of the case studies, an antenna azimuth position control system, is carried throughout the book. The purpose is to illustrate the application of new material in each chapter to the same physical system, thus highlighting the continuity of the design process. Another, more challenging case study, involving

an Unmannered Free-Swimming Submersible Vehicle, is developed over the course of five chapters.

WileyPLUS Content Management System for Students and Professors

WileyPLUS is an online suite of resources, including the full text, for students and instructors. For the sixth edition of *Control Systems Engineering*, this suite offers professors who adopt the book with WileyPLUS the ability to create homework assignments based on algorithmic problems or multi-part questions, which guide the student through a problem. Instructors also have the capability to integrate assets, such as the simulations, into their lecture presentations. Students will find a Read, Study, and Practice zone to help them work through problems based on the ones offered in the text.

Control Solutions (prepared by JustAsk) are included in the WileyPLUS platform. The student will find simulations and Control Solutions in the Read, Study, and Practice zone. The Control Solutions are highlighted in the text with a WileyPLUS icon.

A new addition to the WileyPLUS platform for this edition are National Instruments and Quanser Virtual Laboratories. You will find references to them in sidebar entries throughout the textbook.

Visit www.wiley.com or contact your local Wiley representative for information.

Cyber Exploration Laboratory and Virtual Experiments

Computer experiments using MATLAB, Simulink®3 and the Control System Toolbox are found at the end of the Problems sections under the sub-heading **Cyber Exploration Laboratory**. New to this edition is LabVIEW, which is also used for experiments within the Cyber Exploration Laboratory section of the chapters. The experiments allow the reader to verify the concepts covered in the chapter via simulation. The reader also can change parameters and perform "what if" exploration to gain insight into the effect of parameter and configuration changes. The experiments are written with stated Objectives, Minimum Required Software Packages, as well as Prelab, Lab, and Postlab tasks and questions. Thus, the experiments may be used for a laboratory course that accompanies the class. Cover sheets for these experiments are available at www.wiley.com.college/nise.

In addition, and new to this sixth edition, are **Virtual Experiments**. These experiments are more tightly focused than the **Cyber Exploration Laboratory** experiments and use LabVIEW and Quanser virtual hardware to illustrate immediate discussion and examples. The experiments are referenced in sidebars throughout some chapters.

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[3] Simulink is a registered trademark of The MathWorks, Inc.

(Abundant Illustrations

The ability to visualize concepts and processes is critical to the student's under-
standing. For this reason, approximately 800 photos, diagrams, graphs, and tables
appear throughout the book to illustrate the topics under discussion.

(Numerous End-of-Chapter Problems

Each chapter ends with a variety of homework problems that allow students to test
their understanding of the material presented in the chapter. Problems vary in
degree of difficulty and complexity, and most chapters include several practical, real-
life problems to help maintain students' motivation. Also, the homework problems
contain progressive analysis and design problems that use the same practical systems
to demonstrate the concepts of each chapter.

(Emphasis on Design

Design
D

This textbook places a heavy emphasis on design. Chapters 8, 9, 11, 12 and 13 focus
primarily on design. But. even in chapters that emphasize analysis, simple design
examples are included wherever possible.

Throughout the book, design examples involving physical systems are identi-
fied by the icon shown in the margin. End-of-chapter problems that involve the
design of physical systems are included under the separate heading **Design Problems,**
and also in chapters covering design, under the heading **Progressive Analysis and
Design Problems.** In these examples and problems, a desired response is specified,
and the student must evaluate certain system parameters, such as gain, or specify a
system configuration along with parameter values. In addition, the text includes
numerous design examples and problems (not identified by an icon) that involve
purely mathematical systems.

Because visualization is so vital to understanding design, this text carefully
relates indirect design specifications to more familiar ones. For example, the less
familiar and indirect phase margin is carefully related to the more direct and familiar
percent overshoot before being used as a design specification.

For each general type of design problem introduced in the text, a methodology
for solving the problem is presented—in many cases in the form of a step-by-step
procedure, beginning with a statement of design objectives. Example problems serve
to demonstrate the methodology by following the procedure, making simplifying
assumptions, and presenting the results of the design in tables or plots that compare
the performance of the original system to that of the improved system. This
comparison also serves as a check on the simplifying assumptions.

Transient response design topics are covered comprehensively in the text. They
include:

- Design via gain adjustment using the root locus
- Design of compensation and controllers via the root locus
- Design via gain adjustment using sinusoidal frequency response methods
- Design of compensation via sinusoidal frequency response methods

- Design of controllers in state space using pole-placement techniques
- Design of observers in state-space using pole-placement techniques
- Design of digital control systems via gain adjustment on the root locus
- Design of digital control system compensation via s-plane design and the Tustin transformation

Steady-state error design is covered comprehensively in this textbook and includes:

- Gain adjustment
- Design of compensation via the root locus
- Design of compensation via sinusoidal frequency response methods
- Design of integral control in state space

Finally, the design of gain to yield stability is covered from the following perspectives:

- Routh-Hurwitz criterion
- Root locus
- Nyquist criterion
- Bode plots

❰ Flexible Coverage

The material in this book can be adapted for a one-quarter or a one-semester course. The organization is flexible, allowing the instructor to select the material that best suits the requirements and time constraints of the class.

State Space
SS

Throughout the book, state-space methods are presented along with the classical approach. Chapters and sections (as well as examples, exercises, review questions, and problems) that cover state space are marked by the icon shown in the margin and can be omitted without any loss of continuity. Those wishing to add a basic introduction to state-space modeling can include Chapter 3 in the syllabus.

In a one-semester course, the discussions of slate-space analysis in Chapters 4, 5, 6 and 7, as well as state-space design in Chapter 12, can be covered along with the classical approach. Another option is to teach state space separately by gathering the appropriate chapters and sections marked with the **State Space** icon into a single unit that follows the classical approach. In a one-quarter course, Chapter 13, "Digital Control Systems," could be eliminated.

❰ Emphasis on Computer-Aided Analysis and Design

Control systems problems, particularly analysis and design problems using the root locus, can be tedious, since their solution involves trial and error. To solve these problems, students should be given access to computers or programmable calculators configured with appropriate software. In this sixth edition, MATLAB continues to be integrated into the text as an optional feature. In addition, and new to this

edition, we have included LabVIEW as an option to computer-aided analysis and design.

Many problems in this text can be solved with either a computer or a hand-held programmable calculator. For example, students can use the programmable calculator to (1) determine whether a point on the s-plane is also on the root locus, (2) find magnitude and phase frequency response data for Nyquist and Bode diagrams, and (3) convert between the following representations of a second-order system:

- Pole location in polar coordinates
- Pole location in Cartesian coordinates
- Characteristic polynomial
- Natural frequency and damping ratio
- Settling time and percent overshoot
- Peak time and percent overshoot
- Settling time and peak time

Handheld calculators have the advantage of easy accessibility for homework and exams. Please consult Appendix H, located at www.wiley.com/college/nise, for a discussion of computational aids that can be adapted to handheld calculators.

Personal computers are better suited for more computation-intensive applications, such as plotting time responses, root loci, and frequency response curves, as well as finding state-transition matrices. These computers also give the student a real-world environment in which to analyze and design control systems. Those not using MATLAB or LabVIEW can write their own programs or use other programs, such as Program CC. Please consult Appendix H at www.wiley.com/college/nise for a discussion of computational aids that can be adapted for use on computers that do not have MATLAB or LabVIEW installed.

Without access to computers or programmable calculators, students cannot obtain meaningful analysis and design results and the learning experience will be limited.

Icons Identifying Major Topics

WileyPLUS
WPCS
Control Solutions

MATLAB
ML

Simulink
SL

Gui Tool
GUIT

Several icons identify coverage and optional material. The icons are summarized as follows:

Control Solutions for the student are identified with a WileyPLUS icon. These problems, developed by JustAsk, are worked in detail and offer explanations of every facet of the solution.

The MATLAB icon identifies MATLAB discussions, examples, exercises, and problems. MATLAB coverage is provided as an enhancement and is not required to use the text.

The Simulink icon identifies Simulink discussions, examples, exercises, and problems. Simulink coverage is provided as an enhancement and is not required to use the text.

The GUI Tool icon identifies MATLAB GUI Tools discussions, examples, exercises, and problems. The discussion of the tools, which includes the LTI Viewer, the Simulink LTIViewer, and the SISO Design Tool, is provided as an enhancement and is not required to use the text.

Symbolic Math
SM

LabVIEW
LV

State Space
SS

Design
D

The Symbolic Math icon identifies Symbolic Math Toolbox discussions, examples, exercises, and problems. Symbolic Math Toolbox coverage is provided as an enhancement and is not required to use the text.

The LabVIEW icon identifies LabVIEW discussions, examples, exercises, and problems. LabVIEW is provided as an enhancement and is not required to use the text.

The State Space icon highlights state-space discussions, examples, exercises, and problems. State-space material is optional and can be omitted without loss of continuity.

The Design icon clearly identifies design problems involving physical systems.

New to This Edition

The following list describes the key changes in this sixth edition

End-of-chapter problems More than 20% of the end-of-chapter problems are either new or revised. Also, an additional Progressive Analysis and Design Problem has been added at the end of the chapter problems. The new progressive problem analyzes and designs a hybrid electric vehicle.

MATLAB The use of MATLAB for computer-aided analysis and design continues to be integrated into discussions and problems as an optional feature in the sixth edition. The MATLAB tutorial has been updated to MATLAB Version 7.9 (R 2009b), the Control System Toolbox Version 8.4, and the Symbolic Math Toolbox Version 5.3

In addition, MATLAB code continues to be incorporated in the chapters in the form of sidebar boxes entitled TryIt.

Virtual Experiments Virtual experiments, developed by National Instruments and Quanser, are included via sidebar references to experiments on Wiley-PLUS. The experiments are performed with 3-D simulations of Quanser hardware using developed LabVIEW VIs. Virtual Experiments are tightly focused and linked to a discussion or example.

Cyber Exploration Laboratory Experiments using LabVIEW have been added. Cyber Exploration Laboratory experiments are general in focus and are envisioned to be used in an associated lab class.

MATLAB's Simulink The use of Simulink to show the effects of nonlinearities upon the time response of open-loop and closed-loop systems appears again in this sixth edition. We also continue to use Simulink to demonstrate how to simulate digital systems. Finally, the Simulink tutorial has been updated to Simulink 7.4

Chapter 11 Lag-lead compensator design using Nichols charts has been added to Section 11.5.

LabVIEW New to this edition is LabVIEW. A tutorial for this tool is included in Appendix D. LabVIEW is used in Cyber Exploration Laboratory experiments and other problems throughout the textbook.

Book Companion Site (BCS) at www .wiley.com/college/nise

The BCS for the sixth edition includes various student and instructor resources. This free resource can be accessed by going to www.wiley.com/college/nise and clicking on Student Companion Site. Professors also access their password-protected resources on the Instructor Companion Site available through this url. Instructors should contact their Wiley sales representative for access.

For the Student:

- All M-files used in the MATLAB, Simulink, GUI Tools, and Symbolic Math Toolbox tutorials, as well as the TryIt exercises
- Copies of the Cyber Exploration Laboratory experiments for use as experiment cover sheets
- Solutions to the Skill-Assessment Exercises in the text
- LabVIEW Virtual Experiments and LabVIEW VIs used in Appendix D

For the Instructor;

- PowerPoint[®4] files containing the figures from the textbook
- Solutions to end-of-chapter problem sets
- Simulations, developed by JustAsk, for inclusion in lecture presentations

Book Organization by Chapter

Many times it is helpful lo understand an author's reasoning behind the organization of the course material. The following paragraphs hopefully shed light on this topic.

The primary goal of Chapter 1 is to motivate students. In this chapter, students learn about the many applications of control systems in everyday life and about the advantages of study and a career in this field. Control systems engineering design objectives, such as transient response, steady-state error, and stability, are introduced, as is the path to obtaining these objectives. New and unfamiliar terms also are included in the Glossary.

Many students have trouble with an early step in the analysis and design sequence: transforming a physical system into a schematic. This step requires many simplifying assumptions based on experience the typical college student does not yet possess. Identifying some of these assumptions in Chapter 1 helps to fill the experience gap.

Chapters 2, 3, and 5 address the representation of physical systems. Chapters 2 and 3 cover modeling of open-loop systems, using frequency response techniques and state-space techniques, respectively. Chapter 5 discusses the representation and reduction of systems formed of interconnected open-loop subsystems. Only a representative sample of physical systems can be covered in a textbook of this length. Electrical, mechanical (both translational and rotational), and electromechanical systems are used as examples of physical systems that are modeled, analyzed, and designed. Linearization of a nonlinear system—one technique used by the engineer to simplify a system in order to represent it mathematically—is also introduced.

Chapter 4 provides an introduction to system analysis, that is, finding and describing the output response of a system. It may seem more logical to reverse the order of Chapters 4 and 5, to present the material in Chapter 4 along with other chapters covering analysis. However, many years of teaching control systems have taught me that the sooner students see an application of the study of system representation, the higher their motivation levels remain.

Chapters 6, 7, 8, and 9 return to control systems analysis and design with the study of stability (Chapter 6), steady-state errors (Chapter 7), and transient response of higher-order systems using root locus techniques (Chapter 8). Chapter 9 covers design of compensators and controllers using the root locus.

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[4] PowerPoint is a registered trademark of Microsoft Corporation.

Chapters 10 and 11 focus on sinusoidal frequency analysis and design. Chapter 10, like Chapter 8, covers basic concepts for stability, transient response, and steady-state-error analysis. However, Nyquist and Bode methods are used in place of root locus. Chapter 11, like Chapter 9, covers the design of compensators, but from the point of view of sinusoidal frequency techniques rather than root locus.

An introduction to state-space design and digital control systems analysis and design completes the text in Chapters 12 and 13, respectively. Although these chapters can be used as an introduction for students who will be continuing their study of control systems engineering, they are useful by themselves and as a supplement to the discussion of analysis and design in the previous chapters. The subject matter cannot be given a comprehensive treatment in two chapters, but the emphasis is clearly outlined and logically linked to the rest of the book.

◖ Acknowledgments

worked behind the scenes, but who should be thanked never the less. Rather than repeating their names and titles here, I refer the reader to the copyright page of this book where they are listed and credited. I am very thankful for their contributions.

Next, I want to acknowledge Integra Software Services, Inc. and its staff for turning the sixth edition manuscript into the finished product you are holding in your hands. Specifically, kudos go out to Heather Johnson, Managing Editor, who, once again, was always there to address my concerns in a timely and professional manner.

My sincere appreciation is extended to Erik Luther of National Instruments Corporation and Paul Gilbert and Michel Levis of Quanser for conceiving, coordinating, and developing the Virtual Experiments that I am sure will enhance your understanding of control systems.

Finally, last but certainly not least, I want to express my appreciation to my wife, Ellen, for her support in ways too numerous to mention during the writing of the past six editions. Specifically though, thanks to her proofing final pages for this sixth edition, you the reader hopefully will find comprehension rather than apprehension in the pages that follow.

Norman S. Nise

Introduction

1
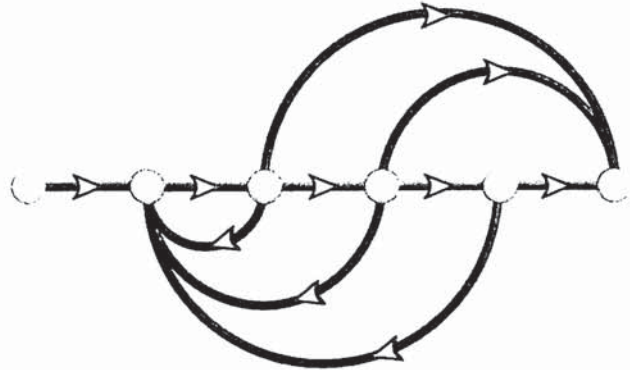
(Chapter Learning Outcomes)

After completing this chapter, the student will be able to:

- Define a control system and describe some applications (Section 1.1)
- Describe historical developments leading to modern day control theory (Section 1.2)
- Describe the basic features and configurations of control systems (Section 1.3)
- Describe control systems analysis and design objectives (Section 1.4)
- Describe a control system's design process (Sections 1.5–1.6)
- Describe the benefit from studying control systems (Section 1.7)

(Case Study Learning Outcomes)

- You will be introduced to a running case study—an antenna azimuth position control system—that will serve to illustrate the principles in each subsequent chapter. In this chapter, the system is used to demonstrate qualitatively how a control system works as well as to define performance criteria that are the basis for control systems analysis and design.

(1.1 Introduction

Control systems are an integral part of modern society. Numerous applications are all around us: The rockets fire, and the space shuttle lifts off to earth orbit; in splashing cooling water, a metallic part is automatically machined; a self-guided vehicle delivering material to workstations in an aerospace assembly plant glides along the floor seeking its destination. These are just a few examples of the automatically controlled systems that we can create.

We are not the only creators of automatically controlled systems; these systems also exist in nature. Within our own bodies are numerous control systems, such as the pancreas, which regulates our blood sugar. In time of "fight or flight," our adrenaline increases along with our heart rate, causing more oxygen to be delivered to our cells. Our eyes follow a moving object to keep it in view; our hands grasp the object and place it precisely at a predetermined location.

Even the nonphysical world appears to be automatically regulated. Models have been suggested showing automatic control of student performance. The input to the model is the student's available study time, and the output is the grade. The model can be used to predict the time required for the grade to rise if a sudden increase in study time is available. Using this model, you can determine whether increased study is worth the effort during the last week of the term.

Control System Definition

A control system consists of *subsystems* and *processes* (or *plants*) assembled for the purpose of obtaining a desired *output* with desired *performance*, given a specified *input*. Figure 1.1 shows a control system in its simplest form, where the input represents a desired output.
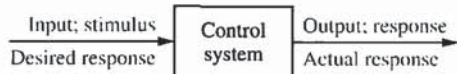
FIGURE 1.1 Simplified description of a control system

For example, consider an elevator. When the fourth-floor button is pressed on the first floor, the elevator rises to the fourth floor with a speed and floor-leveling accuracy designed for passenger comfort. The push of the fourth-floor button is an *input* that represents our desired *output*, shown as a step function in Figure 1.2. The *performance* of the elevator can be seen from the elevator response curve in the figure.

Two major measures of performance are apparent: (1) the transient response and (2) the steady-state error. In our example, passenger comfort and passenger patience are dependent upon the transient response. If this response is too fast, passenger comfort is sacrificed; if too slow, passenger patience is sacrificed. The steady-state error is another important performance specification since passenger safety and convenience would be sacrificed if the elevator did not properly level.
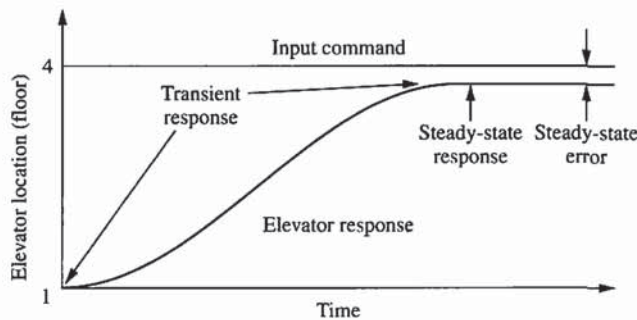
FIGURE 1.2 Elevator response

(a)   (b)
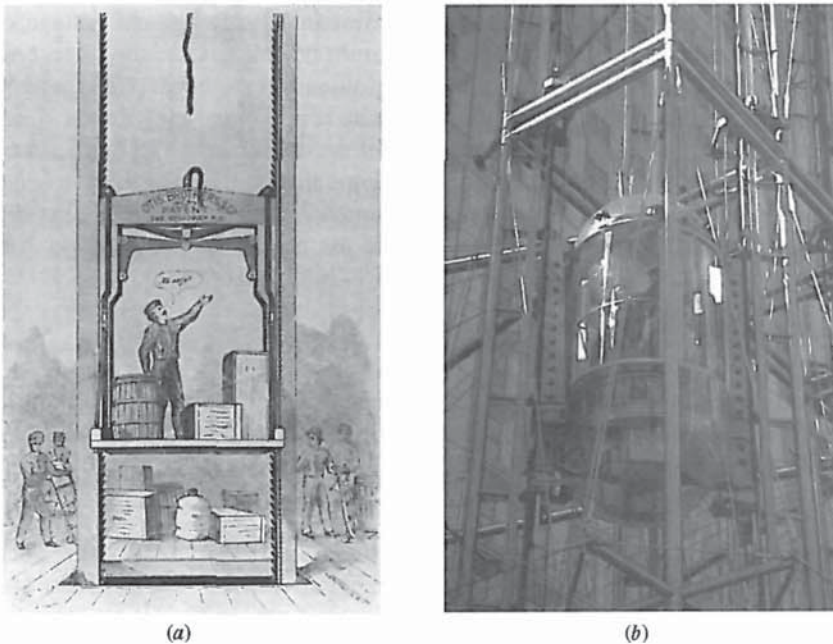
FIGURE 1.3 **a.** Early elevators were controlled by hand ropes or an elevator operator. Here a rope is cut to demonstrate the safety brake, an innovation in early elevators (© Bettman/ Corbis); **b.** One of two modern Duo-lift elevators makes its way up the Grande Arche in Paris. Two elevators are driven by one motor, with each car acting as a counterbalance to the other. Today, elevators are fully automatic, using control systems to regulate position and velocity.

Advantages of Control Systems

With control systems we can move large equipment with precision that would otherwise be impossible. We can point huge antennas toward the farthest reaches of the universe to pick up faint radio signals; controlling these antennas by hand would be impossible. Because of control systems, elevators carry us quickly to our destination, automatically stopping at the right floor (Figure 1.3). We alone could not provide the power required for the load and the speed; motors provide the power, and control systems regulate the position and speed.

We build control systems for four primary reasons:

1. Power amplification
2. Remote control
3. Convenience of input form
4. Compensation for disturbances

For example, a radar antenna, positioned by the low-power rotation of a knob at the input, requires a large amount of power for its output rotation. A control system can produce the needed power amplification, or power *gain*.

Robots designed by control system principles can compensate for human disabilities. Control systems are also useful in remote or dangerous locations. For example, a remote-controlled robot arm can be used to pick up material in a radioactive environment. Figure 1.4 shows a robot arm designed to work in contaminated environments.

Control systems can also be used to provide convenience by changing the form of the input. For example, in a temperature control system, the input is a *position* on a thermostat. The output is *heat*. Thus, a convenient position input yields a desired thermal output.

Another advantage of a control system is the ability to compensate for disturbances. Typically, we control such variables as temperature in
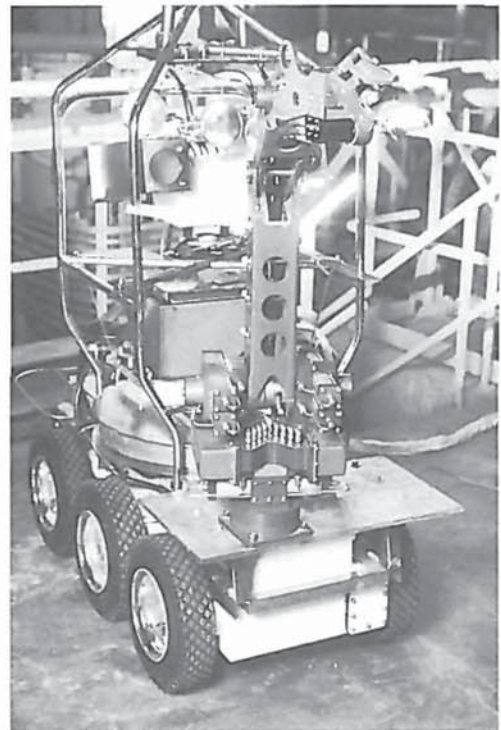
FIGURE 1.4 *Rover* was built to work in contaminated areas at Three Mile Island in Middleton, Pennsylvania, where a nuclear accident occurred in 1979. The remote-controlled robot's long arm can be seen at the front of the vehicle.

thermal systems, position and velocity in mechanical systems, and voltage, current, or frequency in electrical systems. The system must be able to yield the correct output even with a disturbance. For example, consider an antenna system that points in a commanded direction. If wind forces the antenna from its commanded position, or if noise enters internally, the system must be able to detect the disturbance and correct the antenna's position. Obviously, the system's input will not change to make the correction. Consequently, the system itself must measure the amount that the disturbance has repositioned the antenna and then return the antenna to the position commanded by the input.

1.2   A History of Control Systems

Feedback control systems are older than humanity. Numerous biological control systems were built into the earliest inhabitants of our planet. Let us now look at a brief history of human-designed control systems.[1]

Liquid-Level Control

The Greeks began engineering feedback systems around 300 B.C. A water clock invented by Ktesibios operated by having water trickle into a measuring container at a constant rate. The level of water in the measuring container could be used to tell time. For water to trickle at a constant rate, the supply tank had to be kept at a constant level. This was accomplished using a float valve similar to the water-level control in today's flush toilets.

Soon after Ktesibios, the idea of liquid-level control was applied to an oil lamp by Philon of Byzantium. The lamp consisted of two oil containers configured vertically. The lower pan was open at the top and was the fuel supply for the flame. The closed upper bowl was the fuel reservoir for the pan below. The containers were interconnected by two capillary tubes and another tube, called a *vertical riser*, which was inserted into the oil in the lower pan just below the surface. As the oil burned, the base of the vertical riser was exposed to air, which forced oil in the reservoir above to flow through the capillary tubes and into the pan. The transfer of fuel from the upper reservoir to the pan stopped when the previous oil level in the pan was reestablished, thus blocking the air from entering the vertical riser. Hence, the system kept the liquid level in the lower container constant.

Steam Pressure and Temperature Controls

Regulation of steam pressure began around 1681 with Denis Papin's invention of the safety valve. The concept was further elaborated on by weighting the valve top. If the upward pressure from the boiler exceeded the weight, steam was released, and the pressure decreased. If it did not exceed the weight, the valve did not open, and the pressure inside the boiler increased. Thus, the weight on the valve top set the internal pressure of the boiler.

Also in the seventeenth century, Cornelis Drebbel in Holland invented a purely mechanical temperature control system for hatching eggs. The device used a vial of alcohol and mercury with a floater inserted in it. The floater was connected to a damper that controlled a flame. A portion of the vial was inserted into the incubator to sense the heat generated by the fire. As the heat increased, the alcohol and mercury expanded, raising the floater, closing the damper, and reducing the flame. Lower temperature caused the float to descend, opening the damper and increasing the flame.

Speed Control

In 1745, speed control was applied to a windmill by Edmund Lee. Increasing winds pitched the blades farther back, so that less area was available. As the wind

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[1] See *Bennett* (*1979*) and *Mayr* (*1970*) for definitive works on the history of control systems.

decreased, more blade area was available. William Cubitt improved on the idea in 1809 by dividing the windmill sail into movable louvers.

Also in the eighteenth century, James Watt invented the flyball speed governor to control the speed of steam engines. In this device, two spinning flyballs rise as rotational speed increases. A steam valve connected to the flyball mechanism closes with the ascending flyballs and opens with the descending flyballs, thus regulating the speed.

Stability, Stabilization, and Steering

Control systems theory as we know it today began to crystallize in the latter half of the nineteenth century. In 1868, James Clerk Maxwell published the stability criterion for a third-order system based on the coefficients of the differential equation. In 1874, Edward John Routh, using a suggestion from William Kingdon Clifford that was ignored earlier by Maxwell, was able to extend the stability criterion to fifth-order systems. In 1877, the topic for the Adams Prize was "The Criterion of Dynamical Stability." In response, Routh submitted a paper entitled *A Treatise on the Stability of a Given State of Motion* and won the prize. This paper contains what is now known as the Routh-Hurwitz criterion for stability, which we will study in Chapter 6. Alexandr Michailovich Lyapunov also contributed to the development and formulation of today's theories and practice of control system stability. A student of P. L. Chebyshev at the University of St. Petersburg in Russia, Lyapunov extended the work of Routh to nonlinear systems in his 1892 doctoral thesis, entitled *The General Problem of Stability of Motion.*

During the second half of the 1800s, the development of control systems focused on the steering and stabilizing of ships. In 1874, Henry Bessemer, using a gyro to sense a ship's motion and applying power generated by the ship's hydraulic system, moved the ship's saloon to keep it stable (whether this made a difference to the patrons is doubtful). Other efforts were made to stabilize platforms for guns as well as to stabilize entire ships, using pendulums to sense the motion.

Twentieth-Century Developments

It was not until the early 1900s that automatic steering of ships was achieved. In 1922, the Sperry Gyroscope Company installed an automatic steering system that used the elements of compensation and adaptive control to improve performance. However, much of the general theory used today to improve the performance of automatic control systems is attributed to Nicholas Minorsky, a Russian born in 1885. It was his theoretical development applied to the automatic steering of ships that led to what we call today proportional-plus-integral-plus-derivative (PID), or three-mode, controllers, which we will study in Chapters 9 and 11.

In the late 1920s and early 1930s, H. W. Bode and H. Nyquist at Bell Telephone Laboratories developed the analysis of feedback amplifiers. These contributions evolved into sinusoidal frequency analysis and design techniques currently used for feedback control system, and are presented in Chapters 10 and 11.

In 1948, Walter R. Evans, working in the aircraft industry, developed a graphical technique to plot the roots of a characteristic equation of a feedback system whose parameters changed over a particular range of values. This technique, now known as the root locus, takes its place with the work of Bode and Nyquist in forming the foundation of linear control systems analysis and design theory. We will study root locus in Chapters 8, 9, and 13.

Contemporary Applications

Today, control systems find widespread application in the guidance, navigation, and control of missiles and spacecraft, as well as planes and ships at sea. For example,

modern ships use a combination of electrical, mechanical, and hydraulic components to develop rudder commands in response to desired heading commands. The rudder commands, in turn, result in a rudder angle that steers the ship.

We find control systems throughout the process control industry, regulating liquid levels in tanks, chemical concentrations in vats, as well as the thickness of fabricated material. For example, consider a thickness control system for a steel plate finishing mill. Steel enters the finishing mill and passes through rollers. In the finishing mill, X-rays measure the actual thickness and compare it to the desired thickness. Any difference is adjusted by a screw-down position control that changes the roll gap at the rollers through which the steel passes. This change in roll gap regulates the thickness.

Modern developments have seen widespread use of the digital computer as part of control systems. For example, computers in control systems are for industrial robots, spacecraft, and the process control industry. It is hard to visualize a modern control system that does not use a digital computer.

The space shuttle contains numerous control systems operated by an onboard computer on a time-shared basis. Without control systems, it would be impossible to guide the shuttle to and from earth's orbit or to adjust the orbit itself and support life on board. Navigation functions programmed into the shuttle's computers use data from the shuttle's hardware to estimate vehicle position and velocity. This information is fed to the guidance equations that calculate commands for the shuttle's flight control systems, which steer the spacecraft. In space, the flight control system gimbals (rotates) the orbital maneuvering system (OMS) engines into a position that provides thrust in the commanded direction to steer the spacecraft. Within the earth's atmosphere, the shuttle is steered by commands sent from the flight control system to the aerosurfaces, such as the elevons.

Within this large control system represented by navigation, guidance, and control are numerous subsystems to control the vehicle's functions. For example, the elevons require a control system to ensure that their position is indeed that which was commanded, since disturbances such as wind could rotate the elevons away from the commanded position. Similarly, in space, the gimbaling of the orbital maneuvering engines requires a similar control system to ensure that the rotating engine can accomplish its function with speed and accuracy. Control systems are also used to control and stabilize the vehicle during its descent from orbit. Numerous small jets that compose the reaction control system (RCS) are used initially in the exoatmosphere, where the aerosurfaces are ineffective. Control is passed to the aerosurfaces as the orbiter descends into the atmosphere.

Inside the shuttle, numerous control systems are required for power and life support. For example, the orbiter has three fuel-cell power plants that convert hydrogen and oxygen (reactants) into electricity and water for use by the crew. The fuel cells involve the use of control systems to regulate temperature and pressure. The reactant tanks are kept at constant pressure as the quantity of reactant diminishes. Sensors in the tanks send signals to the control systems to turn heaters on or off to keep the tank pressure constant (*Rockwell International, 1984*).

Control systems are not limited to science and industry. For example, a home heating system is a simple control system consisting of a thermostat containing a bimetallic material that expands or contracts with changing temperature. This expansion or contraction moves a vial of mercury that acts as a switch, turning the heater on or off. The amount of expansion or contraction required to move the mercury switch is determined by the temperature setting.
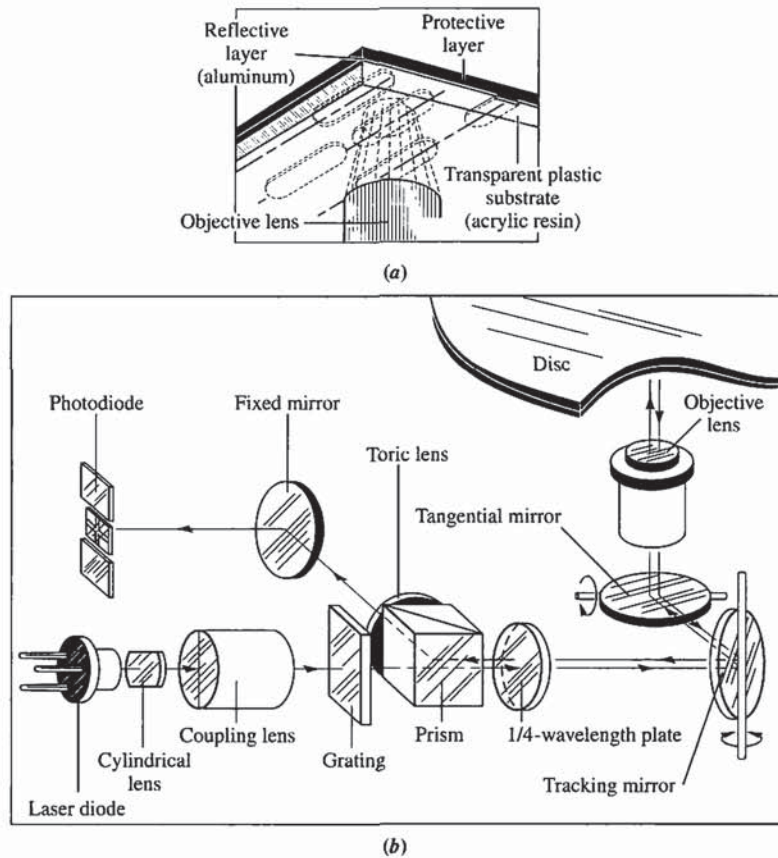
FIGURE 1.5   Optical playback system: **a.** objective lens reading pits on an optical disc; **b.** optical path for playback, showing tracking mirror rotated by a control system to keep the laser beam positioned on the pits (Pioneer Electronics (USA), Inc.)

Home entertainment systems also have built-in control systems. For example, in an optical disk recording system microscopic pits representing the information are burned into the disc by a laser during the recording process. During playback, a reflected laser beam focused on the pits changes intensity (Figure 1.5). The light intensity changes are converted to an electrical signal and processed as sound or picture. A control system keeps the laser beam positioned on the pits, which are cut as concentric circles.

There are countless other examples of control systems, from the everyday to the extraordinary. As you begin your study of control systems engineering, you will become more aware of the wide variety of applications.

1.3   System Configurations

In this section, we discuss two major configurations of control systems: open loop and closed loop. We can consider these configurations to be the internal architecture of the total system shown in Figure 1.1. Finally, we show how a digital computer forms part of a control system's configuration.

Open-Loop Systems

A generic *open-loop system* is shown in Figure 1.6(*a*). It starts with a subsystem called an *input transducer*, which converts the form of the input to that used by the *controller*. The controller drives a *process* or a *plant*. The input is sometimes called the *reference*, while the output can be called the *controlled variable*. Other signals, such as *disturbances*, are shown added to the controller and process outputs via *summing junctions*, which yield the algebraic sum of their input signals using associated signs. For example, the plant can be a furnace or air conditioning system, where the output variable is temperature. The controller in a heating system consists of fuel valves and the electrical system that operates the valves.

The distinguishing characteristic of an open-loop system is that it cannot compensate for any disturbances that add to the controller's driving signal (Disturbance 1 in Figure 1.6(*a*)). For example, if the controller is an electronic amplifier and Disturbance 1 is noise, then any additive amplifier noise at the first summing junction will also drive the process, corrupting the output with the effect of the noise. The output of an open-loop system is corrupted not only by signals that add to the controller's commands but also by disturbances at the output (Disturbance 2 in Figure 1.6(*a*)). The system cannot correct for these disturbances, either.

Open-loop systems, then, do not correct for disturbances and are simply commanded by the input. For example, toasters are open-loop systems, as anyone with burnt toast can attest. The controlled variable (output) of a toaster is the color of the toast. The device is designed with the assumption that the toast will be darker the longer it is subjected to heat. The toaster does not measure the color of the toast; it does not correct for the fact that the toast is rye, white, or sourdough, nor does it correct for the fact that toast comes in different thicknesses.

Other examples of open-loop systems are mechanical systems consisting of a mass, spring, and damper with a constant force positioning the mass. The greater the force, the greater the displacement. Again, the system position will change with a disturbance, such as an additional force, and the system will not detect or correct for the disturbance. Or assume that you calculate the amount of time you need to study
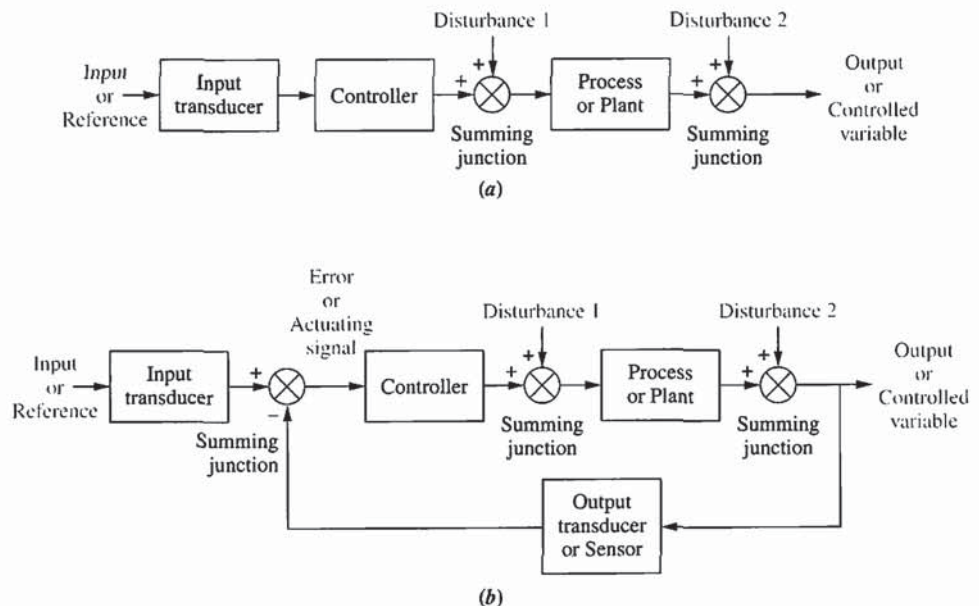
FIGURE 1.6 Block diagrams of control systems: **a.** open-loop system; **b.** closed-loop system

for an examination that covers three chapters in order to get an A. If the professor adds a fourth chapter—a disturbance—you are an open-loop system if you do not detect the disturbance and add study time to that previously calculated. The result of this oversight would be a lower grade than you expected.

Closed-Loop (Feedback Control) Systems

The disadvantages of open-loop systems, namely sensitivity to disturbances and inability to correct for these disturbances, may be overcome in *closed-loop systems*. The generic architecture of a closed-loop system is shown in Figure 1.6(*b*).

The input transducer converts the form of the input to the form used by the controller. An *output transducer*, or *sensor*, measures the output response and converts it into the form used by the controller. For example, if the controller uses electrical signals to operate the valves of a temperature control system, the input position and the output temperature are converted to electrical signals. The input position can be converted to a voltage by a *potentiometer*, a variable resistor, and the output temperature can be converted to a voltage by a *thermistor*, a device whose electrical resistance changes with temperature.

The first summing junction algebraically adds the signal from the input to the signal from the output, which arrives via the *feedback path*, the return path from the output to the summing junction. In Figure 1.6(*b*), the output signal is subtracted from the input signal. The result is generally called the *actuating signal*. However, in systems where both the input and output transducers have *unity gain* (that is, the transducer amplifies its input by 1), the actuating signal's value is equal to the actual difference between the input and the output. Under this condition, the actuating signal is called the *error*.

The closed-loop system compensates for disturbances by measuring the output response, feeding that measurement back through a feedback path, and comparing that response to the input at the summing junction. If there is any difference between the two responses, the system drives the plant, via the actuating signal, to make a correction. If there is no difference, the system does not drive the plant, since the plant's response is already the desired response.

Closed-loop systems, then, have the obvious advantage of greater accuracy than open-loop systems. They are less sensitive to noise, disturbances, and changes in the environment. Transient response and steady-state error can be controlled more conveniently and with greater flexibility in closed-loop systems, often by a simple adjustment of gain (amplification) in the loop and sometimes by redesigning the controller. We refer to the redesign as *compensating* the system and to the resulting hardware as a *compensator*. On the other hand, closed-loop systems are more complex and expensive than open-loop systems. A standard, open-loop toaster serves as an example: It is simple and inexpensive. A closed-loop toaster oven is more complex and more expensive since it has to measure both color (through light reflectivity) and humidity inside the toaster oven. Thus, the control systems engineer must consider the trade-off between the simplicity and low cost of an open-loop system and the accuracy and higher cost of a closed-loop system.

In summary, systems that perform the previously described measurement and correction are called closed-loop, or feedback control, systems. Systems that do not have this property of measurement and correction are called open-loop systems.

Computer-Controlled Systems

In many modern systems, the controller (or compensator) is a digital computer. The advantage of using a computer is that many loops can be controlled or compensated by the same computer through time sharing. Furthermore, any adjustments of the

compensator parameters required to yield a desired response can be made by changes in software rather than hardware. The computer can also perform supervisory functions, such as *scheduling many required applications*. For example, the space shuttle main engine (SSME) controller, which contains two digital computers, alone controls numerous engine functions. It monitors engine sensors that provide pressures, temperatures, flow rates, turbopump speed, valve positions, and engine servo valve actuator positions. The controller further provides closed-loop control of thrust and propellant mixture ratio, sensor excitation, valve actuators, spark igniters, as well as other functions (*Rockwell International, 1984*).

(1.4   Analysis and Design Objectives

In Section 1.1 we briefly alluded to some control system performance specifications, such as transient response and steady-state error. We now expand upon the topic of performance and place it in perspective as we define our analysis and design objectives.

Analysis is the process by which a system's performance is determined. For example, we evaluate its transient response and steady-state error to determine if they meet the desired specifications. *Design* is the process by which a system's performance is created or changed. For example, if a system's transient response and steady-state error are analyzed and found not to meet the specifications, then we change parameters or add additional components to meet the specifications.

A control system is *dynamic:* It responds to an input by undergoing a transient response before reaching a steady-state response that generally resembles the input. We have already identified these two responses and cited a position control system (an elevator) as an example. In this section, we discuss three major objectives of systems analysis and design: producing the desired transient response, reducing steady-state error, and achieving stability. We also address some other design concerns, such as cost and the sensitivity of system performance to changes in parameters.

Transient Response

Transient response is important. In the case of an elevator, a slow transient response makes passengers impatient, whereas an excessively rapid response makes them uncomfortable. If the elevator oscillates about the arrival floor for more than a second, a disconcerting feeling can result. Transient response is also important for structural reasons: Too fast a transient response could cause permanent physical damage. In a computer, transient response contributes to the time required to read from or write to the computer's disk storage (see Figure 1.7). Since reading and writing cannot take place until the head stops, the speed of the read/write head's movement from one track on the disk to another influences the overall speed of the computer.

In this book, we establish quantitative definitions for transient response. We then analyze the system for its *existing* transient response. Finally, we adjust parameters or design components to yield a *desired* transient response—our first analysis and design objective.

FIGURE 1.7 Computer hard disk drive, showing disks and read/write head

Steady-State Response

Another analysis and design goal focuses on the steady-state response. As we have seen, this response resembles the input and is usually what remains after the transients have decayed to zero. For example, this response may be an elevator stopped near the fourth floor or the head of a disk drive finally stopped at the correct track. We are concerned about the accuracy of the steady-state response. An elevator must be level enough with the floor for the passengers to exit, and a read/write head not positioned over the commanded track results in computer errors. An antenna tracking a satellite must keep the satellite well within its beamwidth in order not to lose track. In this text we define steady-state errors quantitatively, analyze a system's steady-state error, and then design corrective action to reduce the steady-state error—our second analysis and design objective.

Stability

Discussion of transient response and steady-state error is moot if the system does not have *stability*. In order to explain stability, we start from the fact that the total response of a system is the sum of the *natural response* and the *forced response*. When you studied linear differential equations, you probably referred to these responses as the *homogeneous* and the *particular solutions*, respectively. Natural response describes the way the system dissipates or acquires energy. The form or nature of this response is dependent only on the system, not the input. On the other hand, the form or nature of the forced response is dependent on the input. Thus, for a *linear* system, we can write

$$\text{Total response} = \text{Natural response} + \text{Forced response} \qquad (1.1)^2$$

For a control system to be useful, the natural response must (1) eventually approach zero, thus leaving only the forced response, or (2) oscillate. In some systems, however, the natural response grows without bound rather than diminish to zero or oscillate. Eventually, the natural response is so much greater than the forced response that the system is no longer controlled. This condition, called *instability*, could lead to self-destruction of the physical device if limit stops are not part of the design. For example, the elevator would crash through the floor or exit through the ceiling; an aircraft would go into an uncontrollable roll; or an antenna commanded to point to a target would rotate, line up with the target, but then begin to oscillate about the target with *growing* oscillations and *increasing* velocity until the motor or amplifiers reached their output limits or until the antenna was damaged structurally. A time plot of an unstable system would show a transient response that grows without bound and without any evidence of a steady-state response.

Control systems must be designed to be stable. That is, their natural response must decay to zero as time approaches infinity, or oscillate. In many systems the transient response you see on a time response plot can be directly related to the natural response. Thus, if the natural response decays to zero as time approaches infinity, the transient response will also die out, leaving only the forced response. If the system is stable, the proper transient response and steady-state error characteristics can be designed. Stability is our third analysis and design objective.

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[2] You may be confused by the words *transient* vs. *natural*, and *steady-state* vs. *forced*. If you look at Figure 1.2, you can see the transient and steady-state portions of the total response as indicated. The transient response is the sum of the natural and forced responses, while the natural response is large. If we plotted the natural response by itself, we would get a curve that is different from the transient portion of Figure 1.2. The steady-state response of Figure 1.2 is also the sum of the natural and forced responses, but the natural response is small. Thus, the transient and steady-state responses are what you actually see on the plot; the natural and forced responses are the underlying mathematical components of those responses.

Other Considerations

The three main objectives of control system analysis and design have already been enumerated. However, *other important considerations must be taken into account.* For example, factors affecting hardware selection, such as motor sizing to fulfill power requirements and choice of sensors for accuracy, must be considered early in the design.

Finances are another consideration. Control system designers cannot create designs without considering their economic impact. Such considerations as budget allocations and competitive pricing must guide the engineer. For example, if your product is one of a kind, you may be able to create a design that uses more expensive components without appreciably increasing total cost. However, if your design will be used for many copies, slight increases in cost per copy can translate into many more dollars for your company to propose during contract bidding and to outlay before sales.

Another consideration is *robust* design. System parameters considered constant during the design for transient response, steady-state errors, and stability change over time when the actual system is built. Thus, the performance of the system also changes over time and will not be consistent with your design. Unfortunately, the relationship between parameter changes and their effect on performance is not linear. In some cases, even in the same system, changes in parameter values can lead to small or large changes in performance, depending on the system's nominal operating point and the type of design used. Thus, the engineer wants to create a robust design so that the system will not be sensitive to parameter changes. We discuss the concept of system sensitivity to parameter changes in Chapters 7 and 8. This concept, then, can be used to test a design for robustness.

(Case Study)

Introduction to a Case Study

Now that our objectives are stated, how do we meet them? In this section we will look at an example of a feedback control system. The system introduced here will be used in subsequent chapters as a running case study to demonstrate the objectives of those chapters. A colored background like this will identify the case study section at the end of each chapter. Section 1.5, which follows this first case study, explores the design process that will help us build our system.

Antenna Azimuth: An Introduction to Position Control Systems

A position control system converts a position input command to a position output response. Position control systems find widespread applications in antennas, robot arms, and computer disk drives. The radio telescope antenna in Figure 1.8 is one example of a system that uses position control systems. In this section, we will look in detail at an antenna azimuth position control system that could be used to position a radio telescope antenna. We will see how the system works and how we can effect changes in its performance. The discussion here will be on a qualitative level, with the objective of getting an intuitive feeling for the systems with which we will be dealing.

An antenna azimuth position control system is shown in Figure 1.9(*a*), with a more detailed layout and schematic in Figures 1.9(*b*) and 1.9(*c*), respectively. Figure 1.9(*d*) shows *a functional block diagram* of the system. The functions are shown above the blocks, and the required hardware is indicated inside the blocks. Parts of Figure 1.9 are repeated on the front endpapers for future reference.
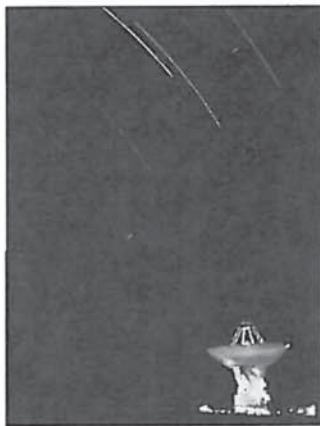
FIGURE 1.8   The search for extraterrestrial life is being carried out with radio antennas like the one pictured here. A radio antenna is an example of a system with position controls.

The purpose of this system is to have the azimuth angle output of the antenna, $\theta_o(t)$, follow the input angle of the potentiometer, $\theta_i(t)$. Let us look at Figure 1.9(*d*) and describe how this system works. The input command is an angular displacement. The potentiometer converts the angular displacement into a voltage.

(*a*)

(*b*)

(*c*)
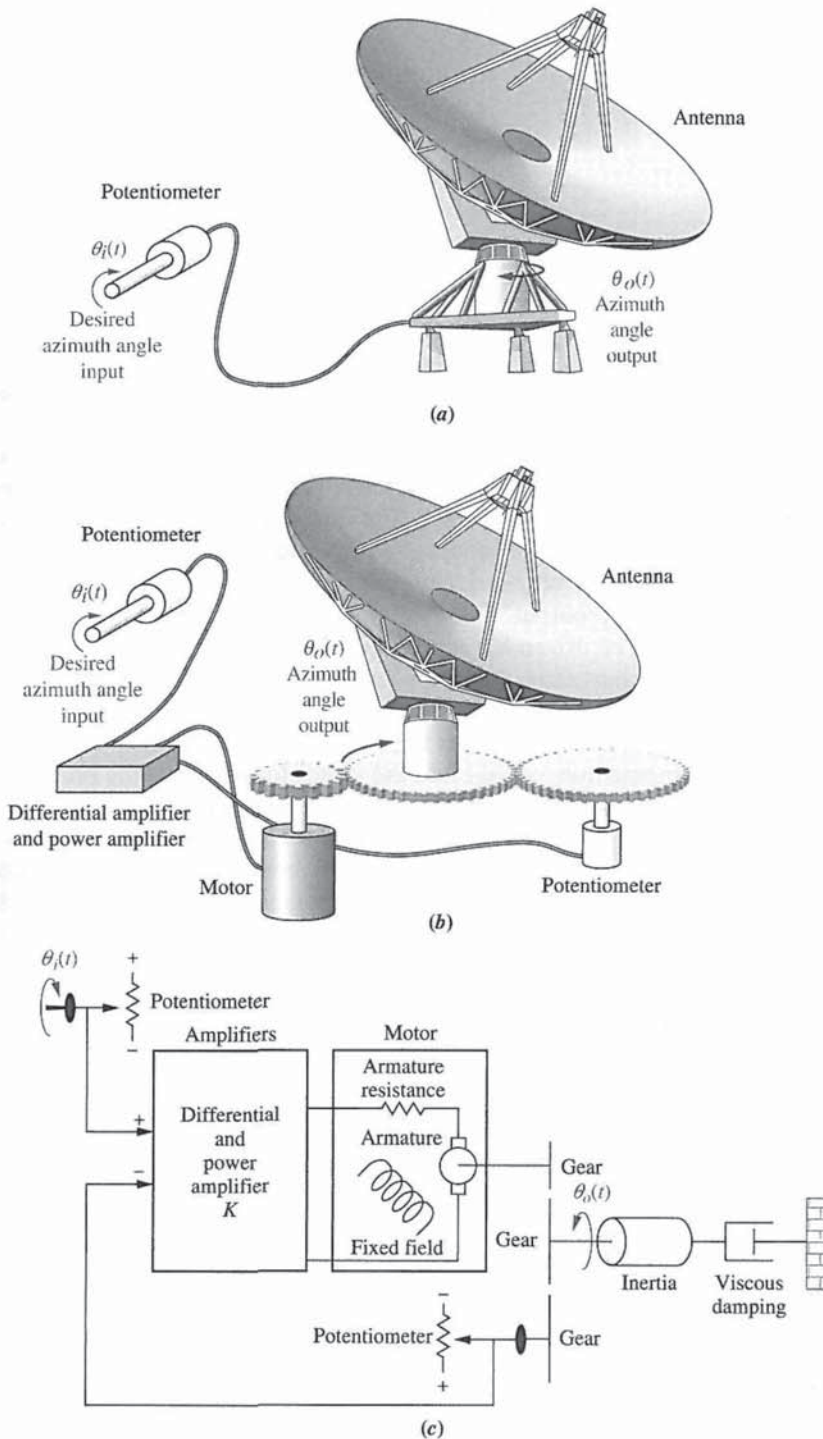
FIGURE 1.9 Antenna azimuth position control system: **a.** system concept; **b.** detailed layout; **c.** schematic; (*figure continues*)

(d)
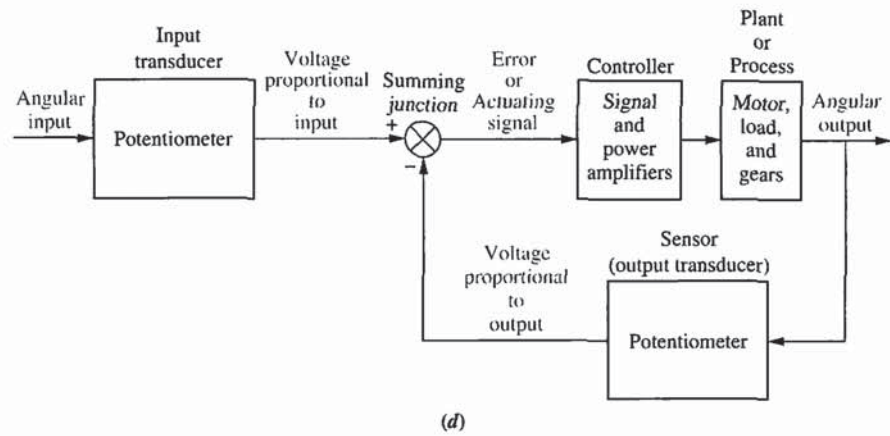
Similarly, the output angular displacement is converted to a voltage by the potentiome-
ter in the feedback path. The signal and power amplifiers boost the difference between
the input and output voltages. This amplified actuating signal drives the plant.

The system normally operates to drive the error to zero. When the input and output
match, the error will be zero, and the motor will not turn. Thus, the motor is driven only
when the output and the input do not match. The greater the difference between the input
and the output, the larger the motor input voltage, and the faster the motor will turn.

If we increase the gain of the signal amplifier, will there be an increase in the
steady-state value of the output? If the gain is increased, then for a given actuating
signal, the motor will be driven harder. However, the motor will still stop when the
actuating signal reaches zero, that is, when the output matches the input. The
difference in the response, however, will be in the transients. Since the motor is
driven harder, it turns faster toward its final position. Also, because of the increased
speed, increased momentum could cause the motor to overshoot the final value and
be forced by the system to return to the commanded position. Thus, the possibility
exists for a transient response that consists of *damped oscillations* (that is, a sinusoidal
response whose amplitude diminishes with time) about the steady-state value if the
gain is high. The responses for low gain and high gain are shown in Figure 1.10.
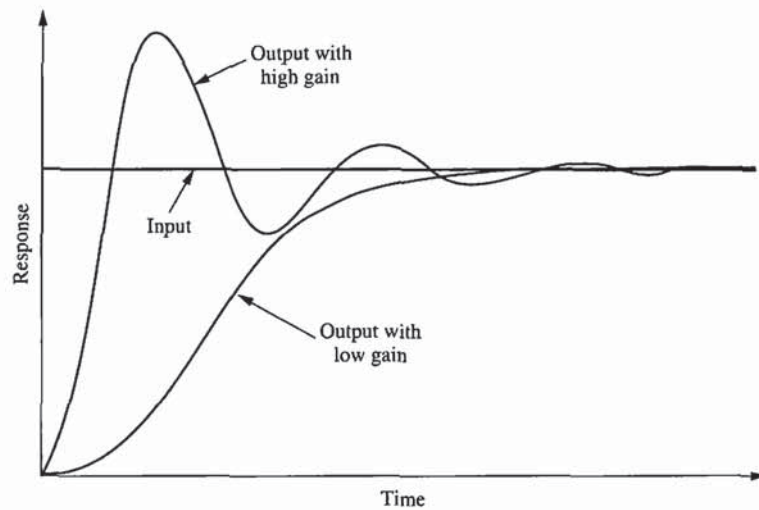
FIGURE 1.10 Response of a
position control system,
showing effect of high and low
controller gain on the output
response

We have discussed the transient response of the position control system. Let us now direct our attention to the steady-state position to see how closely the output matches the input after the transients disappear.

We define steady-state error as the difference between the input and the output after the transients have effectively disappeared. The definition holds equally well for step, ramp, and other types of inputs. Typically, the steady-state error decreases with an increase in gain and increases with a decrease in gain. Figure 1.10 shows zero error in the steady-state response; that is, after the transients have disappeared, the output position equals the commanded input position. In some systems, the steady-state error will not be zero; for these systems, a simple gain adjustment to regulate the transient response is either not effective or leads to a trade-off between the desired transient response and the desired steady-state accuracy.

To solve this problem, a controller with a dynamic response, such as an electrical filter, is used along with an amplifier. With this type of controller, it is possible to design both the required transient response and the required steady-state accuracy without the trade-off required by a simple setting of gain. However, the controller is now more complex. The filter in this case is called a compensator. Many systems also use dynamic elements in the feedback path along with the output transducer to improve system performance.

In summary, then, our design objectives and the system's performance revolve around the transient response, the steady-state error, and stability. Gain adjustments can affect performance and sometimes lead to trade-offs between the performance criteria. Compensators can often be designed to achieve performance specifications without the need for trade-offs. Now that we have stated our objectives and some of the methods available to meet those objectives, we describe the orderly progression that leads us to the final system design.

1.5 The Design Process

In this section, we establish an orderly sequence for the design of feedback control systems that will be followed as we progress through the rest of the book. Figure 1.11 shows the described process as well as the chapters in which the steps are discussed.

The antenna azimuth position control system discussed in the last section is representative of control systems that must be analyzed and designed. Inherent in

Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Determine a physical system and specifications from the requirements.	Draw a functional block diagram.	Transform the physical system into a schematic.	Use the schematic to obtain a block diagram, signal-flow diagram, or state-space representation.	If multiple blocks, reduce the block diagram to a single block or closed-loop system.	Analyze, design, and test to see that requirements and specifications are met.

Analog: Chapter 1   Chapters 2, 3   Chapter 5   Chapters 4, 6–12
Digital: Chapter 13   Chapter 13   Chapter 13

FIGURE 1.11 The control system design process

Figure 1.11 is feedback and communication during each phase. For example, if testing (Step 6) shows that requirements have not been met, the system must be redesigned and retested. Sometimes requirements are conflicting and the design cannot be attained. In these cases, the requirements have to be respecified and the design process repeated. Let us now elaborate on each block of Figure 1.11.

Step 1: Transform Requirements Into a Physical System

We begin by transforming the requirements into a physical system. For example, in the antenna azimuth position control system, the requirements would state the desire to position the antenna from a remote location and describe such features as weight and physical dimensions. Using the requirements, design specifications, such as desired transient response and steady-state accuracy, are determined. Perhaps an overall concept, such as Figure 1.9(a), would result.

Step 2: Draw a Functional Block Diagram

The designer now translates a qualitative description of the system into a functional block diagram that describes the component parts of the system (that is, function and/or hardware) and shows their interconnection. Figure 1.9(d) is an example of a functional block diagram for the antenna azimuth position control system. It indicates functions such as input transducer and controller, as well as possible hardware descriptions such as amplifiers and motors. At this point the designer may produce a detailed layout of the system, such as that shown in Figure 1.9(b), from which the next phase of the analysis and design sequence, developing a schematic diagram, can be launched.

Step 3: Create a Schematic

As we have seen, position control systems consist of electrical, mechanical, and electromechanical components. After producing the description of a physical system, the control systems engineer transforms the physical system into a schematic diagram. The control system designer can begin with the physical description, as contained in Figure 1.9(a), to derive a schematic. The engineer must make approximations about the system and neglect certain phenomena, or else the schematic will be unwieldy, making it difficult to extract a useful mathematical model during the next phase of the analysis and design sequence. The designer starts with a simple schematic representation and, at subsequent phases of the analysis and design sequence, checks the assumptions made about the physical system through analysis and computer simulation. If the schematic is too simple and does not adequately account for observed behavior, the control systems engineer adds phenomena to the schematic that were previously assumed negligible. A schematic diagram for the antenna azimuth position control system is shown in Figure 1.9(c).

When we draw the potentiometers, we make our first simplifying assumption by neglecting their friction or inertia. These mechanical characteristics yield a dynamic, rather than an instantaneous, response in the output voltage. We assume that these mechanical effects are negligible and that the voltage across a potentiometer changes instantaneously as the potentiometer shaft turns.

A differential amplifier and a power amplifier are used as the controller to yield gain and power amplification, respectively, to drive the motor. Again, we assume that the dynamics of the amplifiers are rapid compared to the response time of the motor; thus, we model them as a pure gain, K.

A dc motor and equivalent load produce the output angular displacement. The speed of the motor is proportional to the voltage applied to the motor's *armature circuit*. Both inductance and resistance are part of the armature circuit. In showing

just the armature resistance in Figure 1.9(c), we assume the effect of the armature inductance is negligible for a dc motor.

The designer makes further assumptions about the load. The load consists of a rotating mass and bearing friction. Thus, the model consists of *inertia* and *viscous damping* whose resistive torque increases with speed, as in an automobile's shock absorber or a screen door damper.

The decisions made in developing the schematic stem from knowledge of the physical system, the physical laws governing the system's behavior, and *practical experience*. These decisions are not easy; however, as you acquire more design experience, you will gain the insight required for this difficult task.

Step 4: Develop a Mathematical Model (Block Diagram)

Once the schematic is drawn, the designer uses physical laws, such as Kirchhoff's laws for electrical networks and Newton's law for mechanical systems, along with simplifying assumptions, to model the system mathematically. These laws are

Kirchhoff's voltage law   The sum of voltages around a closed path equals zero.

Kirchhoff's current law   The sum of electric currents flowing from a node equals zero.

Newton's laws   The sum of forces on a body equals zero;[3] the sum of moments on a body equals zero.

Kirchhoff's and Newton's laws lead to mathematical models that describe the relationship between the input and output of dynamic systems. One such model is the *linear, time-invariant differential equation*, Eq. (1.2):

$$
\frac{d^m c(t)}{dt^n} + d_{n-1}\frac{d^{m-1}c(t)}{dt^{n-1}} + \cdots + d_0 c(t) = b_m \frac{d^m r(t)}{dt^m} + b_{m-1}\frac{d^{m-1}r(t)}{dt^{m-1}} + \cdots + b_0 r(t)
$$

$$(1.2)^4$$

Many systems can be approximately described by this equation, which relates the output, $c(t)$, to the input, $r(t)$, by way of the system parameters, a_i and b_j. We assume the reader is familiar with differential equations. Problems and a bibliography are provided at the end of the chapter for you to review this subject.

Simplifying assumptions made in the process of obtaining a mathematical model usually leads to a low-order form of Eq. (1.2). Without the assumptions the system model could be of high order or described with nonlinear, time-varying, or partial differential equations. These equations complicate the design process and reduce the designer's insight. Of course, all assumptions must be checked and all simplifications justified through analysis or testing. If the assumptions for simplification cannot be justified, then the model cannot be simplified. We examine some of these simplifying assumptions in Chapter 2.

In addition to the differential equation, the *transfer function* is another way of mathematically modeling a system. The model is derived from the linear, time-invariant differential equation using what we call the *Laplace transform*. Although the transfer

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[3] Alternately, $\sum$ forces $= Ma$. In this text the force, Ma, will be brought to the left-hand side of the equation to yield $\sum$ forces $= 0$ (D'Alembert's principle). We can then have a consistent analogy between force and voltage, and Kirchhoff's and Newton's laws (that is, $\sum$ forces $= 0$; $\sum$ voltages $= 0$).

[4] The right-hand side of Eq. (1.2) indicates differentiation of the input, $r(t)$. In physical systems, differentiation of the input introduces noise. In Chapters 3 and 5 we show implementations and interpretations of Eq. (1.2) that do not require differentiation of the input.

function can be used only for linear systems, it yields more intuitive information than the *differential equation. We will be able to change system parameters and rapidly sense the* effect of these changes on the system response. The transfer function is also useful in modeling the interconnection of subsystems by forming a block diagram similar to Figure 1.9(*d*) but with a mathematical function inside each block.

Still another model is the *state-space representation*. One advantage of state-space methods is that they can also be used for systems that cannot be described by linear differential equations. Further, state-space methods are used to model systems for simulation on the digital computer. Basically, this representation turns an *n*th-order differential equation into *n* simultaneous first-order differential equations. Let this description suffice for now; we describe this approach in more detail in Chapter 3.

Finally, we should mention that to produce the mathematical model for a system, we require knowledge of the parameter values, such as equivalent resistance, inductance, mass, and damping, which is often not easy to obtain. Analysis, measurements, or specifications from vendors are sources that the control systems engineer may use to obtain the parameters.
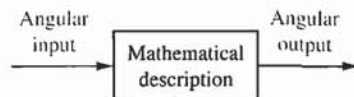
FIGURE 1.12 Equivalent block diagram for the antenna azimuth position control system

Step 5: Reduce the Block Diagram

Subsystem models are interconnected to form block diagrams of larger systems, as in Figure 1.9(*d*), where each block has a mathematical description. Notice that many signals, such as proportional voltages and error, are internal to the system. There are also two signals—*angular input and angular output*—that are external to the system. In order to evaluate system response in this example, we need to reduce this large system's block diagram to a single block with a mathematical description that represents the system from its input to its output, as shown in Figure 1.12. Once the block diagram is reduced, we are ready to analyze and design the system.

Step 6: Analyze and Design

The next phase of the process, following block diagram reduction, is analysis and design. If you are interested only in the performance of an individual subsystem, you can skip the block diagram reduction and move immediately into analysis and design. In this phase, the engineer analyzes the system to see if the response specifications and performance requirements can be met by simple adjustments of system parameters. If specifications cannot be met, the designer then designs additional hardware in order to effect a desired performance.

Test input signals are used, both analytically and during testing, to verify the design. It is neither necessarily practical nor illuminating to choose complicated input signals to analyze a system's performance. Thus, the engineer usually selects standard test inputs. These inputs are impulses, steps, ramps, parabolas, and sinusoids, as shown in Table 1.1.

An *impulse* is infinite at $t = 0$ and zero elsewhere. The area under the unit impulse is 1. An approximation of this type of waveform is used to place initial energy into a *system so that the response due to that initial energy is only the transient response of a* system. From this response the designer can derive a mathematical model of the system.

A *step* input represents a *constant command*, such as position, velocity, or acceleration. Typically, the step input command is of the same form as the output. For example, if the system's output is position, as it is for the antenna azimuth position control system, the step input represents a desired position, and the output represents the actual position. If the system's output is velocity, as is the spindle speed for a video disc player, the step input represents a constant desired speed, and the output represents the actual speed. The designer uses step inputs because both the transient response and the steady-state response are clearly visible and can be evaluated.

TABLE 1.1 Test waveforms used in control systems

Input	Function	Description	Sketch	Use
Impulse	$\delta(t)$	$\delta(t) = \infty$ for $0- < t < 0+$ $= 0$ elsewhere $\int_{0-}^{0+} \delta(t)dt = 1$		Transient response Modeling
Step	$u(t)$	$u(t) = 1$ for $t > 0$ $= 0$ for $t < 0$		Transient response Steady-state error
Ramp	$tu(t)$	$tu(t) = t$ for $t \geq 0$ $= 0$ elsewhere		Steady-state error
Parabola	$\frac{1}{2}t^2u(t)$	$\frac{1}{2}t^2u(t) = \frac{1}{2}t^2$ for $t \geq 0$ $= 0$ elsewhere		Steady-state error
Sinusoid	$\sin \omega t$			Transient response Modeling Steady-state error

The *ramp* input represents a *linearly increasing command*. For example, if the system's output is position, the input ramp represents a linearly increasing position, such as that found when tracking a satellite moving across the sky at constant speed. If the system's output is velocity, the input ramp represents a linearly increasing velocity. The response to an input ramp test signal yields additional information about the steady-state error. The previous discussion can be extended to *parabolic* inputs, which are also used to evaluate a system's steady-state error.

Sinusoidal inputs can also be used to test a physical system to arrive at a mathematical model. We discuss the use of this waveform in detail in Chapters 10 and 11.

We conclude that one of the basic analysis and design requirements is to evaluate the time response of a system for a given input. Throughout the book you will learn numerous methods for accomplishing this goal.

The control systems engineer must take into consideration other characteristics about feedback control systems. For example, control system behavior is altered by fluctuations in component values or system parameters. These variations can be

caused by temperature, pressure, or other environmental changes. Systems must be built so that expected fluctuations do not degrade performance beyond specified bounds. A *sensitivity* analysis can yield the percentage of change in a specification as a function of a change in a system parameter. One of the designer's goals, then, is to build a system with minimum sensitivity over an expected range of environmental changes.

In this section we looked at some control systems analysis and design considerations. We saw that the designer is concerned about transient response, steady-state error, stability, and sensitivity. The text pointed out that although the basis of evaluating system performance is the differential equation, other methods, such as transfer functions and state space, will be used. The advantages of these new techniques over differential equations will become apparent as we discuss them in later chapters.

(1.6 Computer-Aided Design

Now that we have discussed the analysis and design sequence, let us discuss the use of the computer as a computational tool in this sequence. The computer plays an important role in the design of modern control systems. In the past, control system design was labor intensive. Many of the tools we use today were implemented through hand calculations or, at best, using plastic graphical aid tools. The process was slow, and the results not always accurate. Large mainframe computers were then used to simulate the designs.

Today we are fortunate to have computers and software that remove the drudgery from the task. At our own desktop computers, we can perform analysis, design, and simulation with one program. With the ability to simulate a design rapidly, we can easily make changes and immediately test a new design. We can play what-if games and try alternate solutions to see if they yield better results, such as reduced sensitivity to parameter changes. We can include nonlinearities and other effects and test our models for accuracy.

MATLAB

The computer is an integral part of modern control system design, and many computational tools are available for your use. In this book we use MATLAB and the MATLAB Control System Toolbox, which expands MATLAB to include control system–specific commands. In addition, presented are several MATLAB enhancements that give added functionality to MATLAB and the Control Systems Toolbox. Included are (1) Simulink, which uses a graphical user interface (GUI); (2) the LTI Viewer, which permits measurements to be made directly from time and frequency response curves; (3) the SISO Design Tool, a convenient and intuitive analysis and design tool; and (4) the Symbolic Math Toolbox, which saves labor when making symbolic calculations required in control system analysis and design. Some of these enhancements may require additional software available from The MathWorks, Inc.

MATLAB is presented as an alternate method of solving control system problems. You are encouraged to solve problems first by hand and then by MATLAB so that insight is not lost through mechanized use of computer programs. To this end, many examples throughout the book are solved by hand, followed by suggested use of MATLAB.

As an enticement to begin using MATLAB, simple program statements that you can try are suggested throughout the chapters at appropriate locations. Throughout the book, various icons appear in the margin to identify MATLAB references that direct you to the proper program in the proper appendix and tell you what you

will learn. Selected end-of-chapter problems and Case Study Challenges to be solved using MATLAB have also been marked with appropriate icons. The following list itemizes the specific components of MATLAB used in this book, the icon used to identify each, and the appendix in which a description can be found:

MATLAB/Control System Toolbox tutorials and code are found in Appendix B and identified in the text with the MATLAB icon shown in the margin.

MATLAB
ML

Simulink tutorials and diagrams are found in Appendix C and identified in the text with the Simulink icon shown in the margin.

Simulink
SL

MATLAB GUI tools, tutorials, and examples are in Appendix E at www.wiley.com/college/nise and identified in the text with the GUI Tool icon shown in the margin. These tools consist of the LTI Viewer and the SISO Design Tool.

Gui Tool
GUIT

Symbolic Math Toolbox tutorials and code are found in Appendix F at www.wiley.com/college/nise and identified in the text with the Symbolic Math icon shown in the margin.

Symbolic Math
SM

MATLAB code itself is not platform specific. The same code runs on PCs and workstations that support MATLAB. Although there are differences in installing and managing MATLAB files, we do not address them in this book. Also, there are many more commands in MATLAB and the MATLAB toolboxes than are covered in the appendixes. Please explore the bibliographies at the end of the applicable appendixes to find out more about MATLAB file management and MATLAB instructions not covered in this textbook.

LabVIEW

LabVIEW is a programming environment presented as an alternative to MATLAB. This graphical alternative produces front panels of virtual instruments on your computer that are pictorial reproductions of hardware instruments, such as waveform generators or oscilloscopes. Underlying the front panels are block diagrams. The blocks contain underlying code for the controls and indicators on the front panel. Thus, a knowledge of coding is not required. Also, parameters can be easily passed or viewed from the front panel.

A LabVIEW tutorial is in Appendix D and all LabVIEW material is identified with the LabVIEW icon shown in the margin.

LabVIEW
LV

You are encouraged to use computational aids throughout this book. Those not using MATLAB or LabVIEW should consult Appendix H at www.wiley.com/college/nise for a discussion of other alternatives. Now that we have introduced control systems to you and established a need for computational aids to perform analysis and design, we will conclude with a discussion of your career as a control systems engineer and look at the opportunities and challenges that await you.

◖ 1.7 The Control Systems Engineer

Control systems engineering is an exciting field in which to apply your engineering talents, because it cuts across numerous disciplines and numerous functions within those disciplines. The control engineer can be found at the top level of large projects, engaged at the conceptual phase in determining or implementing

overall system requirements. These requirements include total system performance specifications, subsystem functions, and the interconnection of these functions, including interface requirements, hardware and software design, and test plans and procedures.

Many engineers are engaged in only one area, such as circuit design or software development. However, as a control systems engineer, you may find yourself working in a broad arena and interacting with people from numerous branches of engineering and the sciences. For example, if you are working on a biological system, you will need to interact with colleagues in the biological sciences, mechanical engineering, electrical engineering, and computer engineering, not to mention mathematics and physics. You will be working with these engineers at all levels of *project development from concept through design and, finally, testing. At the design* level, the control systems engineer can be performing hardware selection, design, and interface, including total subsystem design to meet specified requirements. The control engineer can be working with sensors and motors as well as electronic, pneumatic, and hydraulic circuits.

The space shuttle provides another example of the diversity required of the systems engineer. In the previous section, we showed that the space shuttle's control systems cut across many branches of science: orbital mechanics and propulsion, aerodynamics, electrical engineering, and mechanical engineering. Whether or not you work in the space program, as a control systems engineer you will apply broad-based knowledge to the solution of engineering control problems. You will have the opportunity to expand your engineering horizons beyond your university curriculum.

You are now aware of future opportunities. But for now, what advantages does this course offer to a student of control systems (other than the fact that you need it to graduate)? Engineering curricula tend to emphasize *bottom-up* design. That is, you start from the components, develop circuits, and then assemble a product. In *top-down* design, a high-level picture of the requirements is first formulated; then the functions and hardware required to implement the system are determined. You will be able to take a top-down systems approach as a result of this course.

A major reason for not teaching top-down design throughout the curriculum is the high level of mathematics initially required for the systems approach. For example, control systems theory, which requires differential equations, could not be taught as a lower-division course. However, while progressing through bottom-up design courses, it is difficult to see how such design fits logically into the large picture of the product development cycle.

After completing this control systems course, you will be able to stand back and see how your previous studies fit into the large picture. Your amplifier course or vibrations course will take on new meaning as you begin to see the role design work plays as part of product development. For example, as engineers, we want to describe the physical world mathematically so that we can create systems that will benefit humanity. You will find that you have indeed acquired, through your previous courses, the ability to model physical systems mathematically, although at the time you might not have understood where in the product development cycle the modeling fits. This course will clarify the analysis and design procedures and show you how the knowledge you acquired fits into the total picture of system design.

Understanding control systems enables students from all branches of engineering to speak a common language and develop an appreciation and working knowledge of the other branches. You will find that there really is not much difference among the branches of engineering as far as the goals and applications are concerned. As you study control systems, you will see this commonality.

(Summary)

Control systems contribute to every aspect of modern society. In our homes we find them in everything from toasters to heating systems to VCRs. Control systems also have widespread applications in science and industry, from steering ships and planes to guiding missiles and the space shuttle. Control systems also exist naturally; our bodies contain numerous control systems. Even economic and psychological system representations have been proposed based on control system theory. Control systems are used where power gain, remote control, or conversion of the form of the input is required.

A control system has an *input*, a *process*, and an *output*. Control systems can be *open loop* or *closed loop*. Open-loop systems do not monitor or correct the output for disturbances; however, they are simpler and less expensive than closed-loop systems. Closed-loop systems monitor the output and compare it to the input. If an error is detected, the system corrects the output and hence corrects the effects of disturbances.

Control systems analysis and design focuses on three primary objectives:

1. Producing the desired transient response
2. Reducing steady-state errors
3. Achieving stability

A system must be stable in order to produce the proper transient and steady-state response. Transient response is important because it affects the speed of the system and influences human patience and comfort, not to mention mechanical stress. Steady-state response determines the accuracy of the control system; it governs how closely the output matches the desired response.

The design of a control system follows these steps:

Step 1   Determine a physical system and specifications from requirements.

Step 2   Draw a functional block diagram.

Step 3   Represent the physical system as a schematic.

Step 4   Use the schematic to obtain a mathematical model, such as a block diagram.

Step 5   Reduce the block diagram.

Step 6   Analyze and design the system to meet specified requirements and specifications that include stability, transient response, and steady-state performance.

In the next chapter we continue through the analysis and design sequence and learn how to use the schematic to obtain a mathematical model.

(Review Questions)

1. Name three applications for feedback control systems.
2. Name three reasons for using feedback control systems and at least one reason for not using them.
3. Give three examples of open-loop systems.
4. Functionally, how do closed-loop systems differ from open-loop systems?
5. State one condition under which the error signal of a feedback control system would not be the difference between the input and the output.

6. If the error signal is not the difference between input and output, by what general name can we describe the error signal?

7. Name two advantages of having a computer in the loop.

8. Name the three major design criteria for control systems.

9. Name the two parts of a system's response.

10. Physically, what happens to a system that is unstable?

11. Instability is attributable to what part of the total response?

12. Describe a typical control system analysis task.

13. Describe a typical control system design task.

14. Adjustments of the forward path gain can cause changes in the transient response. True or false?

15. Name three approaches to the mathematical modeling of control systems.

16. Briefly describe each of your answers to Question 15.

Problems

1. A variable resistor, called a *potentiometer*, is shown in Figure P1.1. The resistance is varied by moving a wiper arm along a fixed resistance. The resistance from A to C is fixed, but the resistance from B to C varies with the position of the wiper arm. If it takes 10 turns to move the wiper arm from A to C, draw a block diagram of the potentiometer showing the input variable, the output variable, and (inside the block) the gain, which is a constant and is the amount by which the input is multiplied to obtain the output. [Section 1.4: Introduction to a Case Study]

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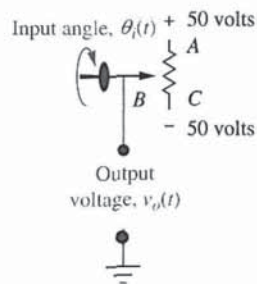
FIGURE P1.1 Potentiometer

2. A temperature control system operates by sensing the difference between the thermostat setting and

the actual temperature and then opening a fuel valve an amount proportional to this difference. Draw a functional closed-loop block diagram similar to Figure 1.9(d) identifying the input and output transducers, the controller, and the plant. Further, identify the input and output signals of all subsystems previously described. [Section 1.4: Introduction to a Case Study]

3. An aircraft's attitude varies in roll, pitch, and yaw as defined in Figure P1.2. Draw a functional block diagram for a closed-loop system that stabilizes the roll as follows: The system measures the actual roll angle with a gyro and compares the actual roll angle with the desired roll angle. The ailerons respond to the roll-angle error by undergoing an angular deflection. The aircraft responds to this angular deflection, producing a roll angle rate. Identify the input and output transducers, the controller, and the plant. Further, identify the nature of each signal. [Section 1.4: Introduction to a Case Study]

FIGURE P1.2 Aircraft attitude defined

4. Many processes operate on rolled material that moves from a supply reel to a take-up reel. Typically, these systems, called *winders*, control the material so that it travels at a constant velocity. Besides velocity, complex winders also control tension, 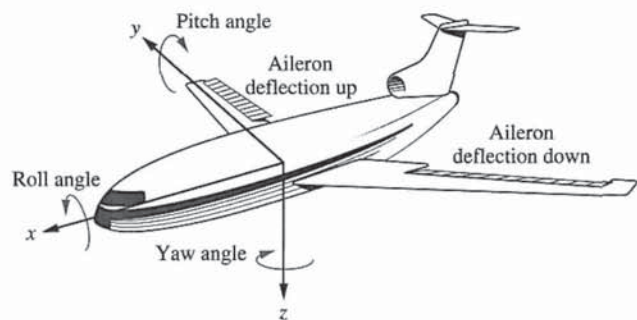compensate for roll inertia while accelerating or decelerating, and regulate acceleration due to sudden changes. A winder is shown in Figure P1.3. The force transducer measures tension; the winder pulls against the nip rolls, which provide an opposing force; and the bridle provides slip. In order to compensate for changes in speed, the material is looped around a *dancer*. The loop prevents rapid changes from causing excessive slack or damaging the material. If the dancer position is sensed by a potentiometer or other device, speed variations due to buildup on the take-up reel or other causes can be controlled by comparing the potentiometer voltage to the commanded speed. The system then corrects the speed and resets the dancer to the desired position (*Ayers, 1988*). Draw a functional block diagram for the speed control system, showing each component and signal. [Section 1.4: Introduction to a Case Study]
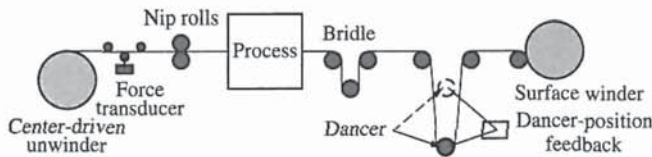

FIGURE P1.3   Winder

5. In a nuclear power generating plant, heat from a reactor is used to generate steam for turbines. The rate of the fission reaction determines the amount of heat generated, and this rate is controlled by rods inserted into the radioactive core. The rods regulate the flow of neutrons. If the rods are lowered into the core, the rate of fission will diminish; if the rods are raised, the fission rate will increase. By automatically
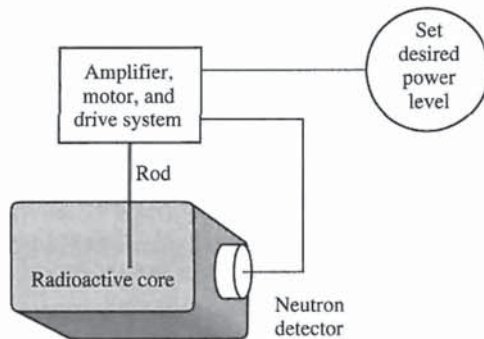

FIGURE P1.4   Control of a nuclear reactor

controlling the position of the rods, the amount of heat generated by the reactor can be regulated. Draw a functional block diagram for the nuclear reactor control system shown in Figure P1.4. Show all blocks and signals. [Section 1.4: Introduction to a Case Study]

6. A university wants to establish a control system model that represents the student population as an output, with the desired student population as an input. The administration determines the rate of admissions by comparing the current and desired student populations. The admissions office then uses this rate to admit students. Draw a functional block diagram showing the administration and the admissions office as blocks of the system. Also show the following signals: the desired student population, the actual student population, the desired student rate as determined by the administration, the actual student rate as generated by the admissions office, the dropout rate, and the net rate of influx. [Section 1.4: Introduction to a Case Study]

7. We can build a control system that will automatically adjust a motorcycle's radio volume as the noise generated by the motorcycle changes. The noise generated by the motorcycle increases with speed. As the noise increases, the system increases the volume of the radio. Assume that the amount of noise can be represented by a voltage generated by the speedometer cable, and the volume of the radio is controlled by a dc voltage (*Hogan, 1988*). If the dc voltage represents the desired volume disturbed by the motorcycle noise, draw the functional block diagram of the automatic volume control system, showing the input transducer, the volume control circuit, and the speed transducer as blocks. Also show the following signals: the desired volume as an input, the actual volume as an output, and voltages representing speed, desired volume, and actual volume. [Section 1.4: Introduction to a Case Study]

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8. Your bathtub at home is a control system that keeps the water level constant. A constant flow from the tap yields a constant water level, because the flow rate through the drain increases as the water level increases, and decreases as the water level decreases. After equilibrium has been reached, the level can be controlled by controlling the input flow rate. A low input flow rate yields a lower level, while a higher input flow rate yields a higher level. [Section 1.4: Introduction to a Case Study]

a. Sketch a control system that uses this principle to precisely control the fluid level in a tank. Show the intake and drain valves, the tank, any sensors and transducers, and the interconnection of all components.

b. Draw a functional block diagram of the system, identifying the input and output signals of each block.

9. A dynamometer is a device used to measure torque and speed and to vary the load on rotating devices. The dynamometer operates as follows to control the amount of torque: A hydraulic actuator attached to the axle presses a tire against a rotating flywheel. The greater the displacement of the actuator, the more force that is applied to the rotating flywheel. A strain gage load cell senses the force. The displacement of the actuator is controlled by an electrically operated valve whose displacement regulates fluid flowing into the actuator (*D'Souza, 1988*). Draw a functional block diagram of a closed-loop system that uses the described dynamometer to regulate the force against the tire during testing. Show all signals and systems. Include amplifiers that power the valve, the valve, the actuator and load, and the tire. [Section 1.4: Introduction to a Case Study]

10. During a medical operation an anesthesiologist controls the depth of unconsciousness by controlling the concentration of isoflurane in a vaporized mixture with oxygen and nitrous oxide. The depth of anesthesia is measured by the patient's blood pressure. The anesthesiologist also regulates ventilation, fluid balance, and the administration of other drugs. In order to free the anesthesiologist to devote more time to the latter tasks, and in the interest of the patient's safety, we wish to automate the depth of anesthesia by automating the control of isoflurane concentration. Draw a functional block diagram of the system showing pertinent signals and subsystems (*Meier, 1992*). [Section 1.4: Introduction to a Case Study]

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11. The vertical position, $x(t)$, of the grinding wheel shown in Figure P1.5 is controlled by a closed-loop system. The input to the system is the desired depth of grind, and the output is the actual depth of grind. The difference between the desired depth and the actual depth drives the motor, resulting in a force applied to the work. This force results in a feed velocity for the grinding wheel (*Jenkins, 1997*). Draw a closed-loop functional block diagram for the grinding process, showing the input, output, force, and grinder feed rate. [Section 1.4: Introduction to a Case Study]
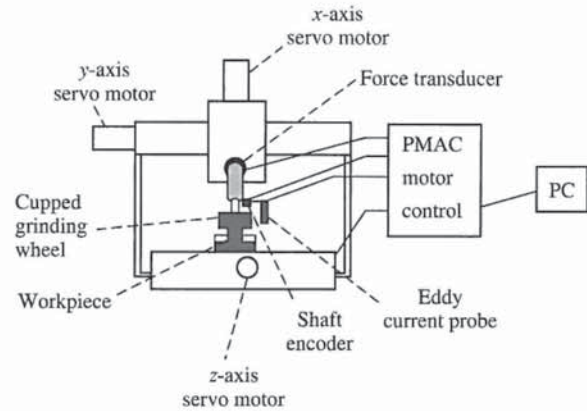
FIGURE P1.5 Grinder system (Reprinted with permission of ASME.)

12. A high-speed proportional solenoid valve is shown in Figure P1.6. A voltage proportional to the desired position of the spool is applied to the coil. The resulting magnetic field produced by the current in the coil causes the armature to move. A push pin connected to the armature moves the spool. A linear voltage differential transformer (LVDT) that outputs a voltage proportional to displacement senses the spool's position. This voltage can be used in a feedback path to implement closed-loop operation (*Vaughan, 1996*). Draw a functional block diagram of the valve, showing input and output positions, coil voltage, coil current, and spool force. [Section 1.4: Introduction to a Case Study]

FIGURE P1.6 High-speed proportional solenoid valve (Reprinted with permission of ASME.)

13. The human eye has a biological control system that varies the pupil diameter to maintain constant light

intensity to the retina. As the light intensity increases, the optical nerve sends a signal to the brain, which commands internal eye muscles to decrease the pupil's eye diameter. When the light intensity decreases, the pupil diameter increases.
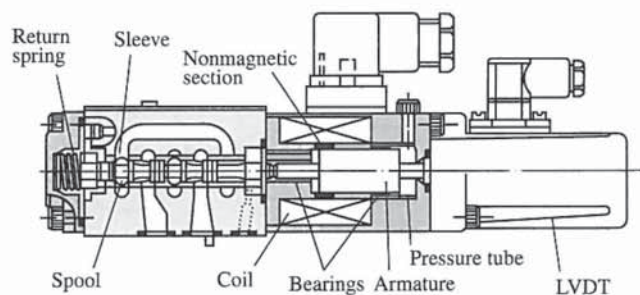
a. Draw a functional block diagram of the light-pupil system indicating the input, output, and intermediate signals; the sensor; the controller; and the actuator. [Section 1.4: Introduction to a Case Study]

b. Under normal conditions the incident light will be larger than the pupil, as shown in Figure P1.7(*a*). If the incident light is smaller than the diameter of the pupil as shown in Figure P1.7(*b*), the feedback path is broken (*Bechhoefer, 2005*). Modify your block diagram from Part **a.** to show where the loop is broken. What will happen if the narrow beam of light varies in intensity, say in a sinusoidal fashion?

c. It has been found (*Bechhoefer, 2005*) that it takes the pupil about 300 milliseconds to react to a change in the incident light. If light shines off center to the retina as shown in Figure P1.7(*c*), describe the response of the pupil with delay present and then without delay present.
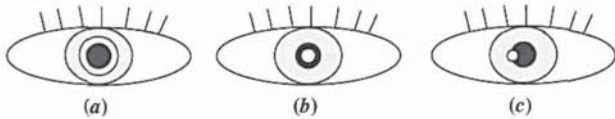

(*a*)   (*b*)   (*c*)

FIGURE P1.7 Pupil is shown black; light beam is shown white. **a.** Light beam diameter is larger than pupil. **b.** Light beam diameter is smaller than pupil. **c.** Narrow light beam is illuminated at pupil's edge.

14. A Segway®[6] Personal Transporter (PT) (Figure P1.8) is a two-wheeled vehicle in which the human operator stands vertically on a platform. As the driver leans left, right, forward, or backward, a set of sensitive gyroscopic sensors sense the desired input. These signals are fed to a computer that amplifies them and commands motors to propel the vehicle in the desired direction. One very important feature of the PT is its safety: The system will maintain its vertical position within a specified angle despite road disturbances, such as uphills and downhills or even if the operator over-leans in any direction. Draw

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[6] Segway is a registered trademark of Segway, Inc. in the United States and/or other countries.

a functional block diagram of the PT system that keeps the system in a vertical position. Indicate the input and output signals, intermediate signals, and main subsystems. (http://segway.com)

FIGURE P1.8 The Segway Personal Transporter (PT)

15. In humans, hormone levels, alertness, and core body temperature are synchronized through a 24-hour circadian cycle. Daytime alertness is at its best when sleep/wake cycles are in synch with the circadian cycle. Thus alertness can be easily affected with a distributed work schedule, such as the one to which astronauts are subjected. It has been shown that the human circadian cycle can be delayed or advanced through light stimulus. To ensure optimal alertness, a system is designed to track astronauts' circadian cycles and increase the quality of sleep during missions. Core body temperature can be used as an indicator of the circadian cycle. A computer model with optimum circadian body temperature variations can be compared to an astronaut's body temperatures. Whenever a difference is detected, the astronaut is subjected to a light stimulus to advance or delay the astronaut's circadian cycle (*Mott, 2003*). Draw a functional block diagram of the system. Indicate the input and output signals, intermediate signals, and main subsystems.

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Control Solutions

16. Tactile feedback is an important component in the learning of motor skills such as dancing, sports, and physical rehabilitation. A suit with white dots recognized by a vision system to determine arm joint positions with millimetric precision was developed. This suit is worn by both teacher and

student to provide position information. (*Lieberman, 2007*). If there is a difference between the teacher's positions and that of the student, vibrational feedback is provided to the student through 8 strategically placed vibrotactile actuators in the wrist and arm, which take advantage of a sensory effect known as *cutaneous rabbit* that tricks the subject to feel uniformly spaced stimuli in places where the actuators are not present. These stimuli help the student adjust to correct the motion. In summary, the system consists of an instructor and a student having their movements followed by the vision system. Their movements are fed into a computer that finds the differences between their joint positions and provides proportional vibrational strength feedback to the student. Draw a block diagram describing the system design.

17. Given the electric network shown in Figure P1.9. [Review]

    a. Write the differential equation for the network if $v(t) = u(t)$, a unit step.

    b. Solve the differential equation for the current, $i(t)$, if there is no initial energy in the network.
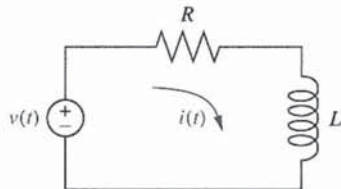
    c. Make a plot of your solution if $R/L = 1$.

FIGURE P1.9   *RL* network

18. Repeat Problem 17 using the network shown in Figure P1.10. Assume $R = 2\,\Omega$, $L = 1$ H, and $1/LC = 25$. [Review]
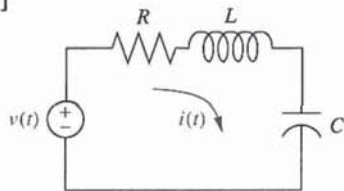

FIGURE P1.10   *RLC* network

19. Solve the following differential equations using classical methods. Assume zero initial conditions. [Review]

    a. $\dfrac{dx}{dt} + 7x = 5\cos 2t$

    b. $\dfrac{d^2x}{dt^2} + 6\dfrac{dx}{dt} + 8x = 5\sin 3t$

    c. $\dfrac{d^2x}{dt^2} + 8\dfrac{dx}{dt} + 25x = 10u(t)$

20. Solve the following differential equations using classical methods and the given initial conditions: [Review]

    a. $\dfrac{d^2x}{dt^2} + 2\dfrac{dx}{dt} + 2x = \sin 2t$

    $x(0) = 2;\ \dfrac{dx}{dt}(0) = -3$

    b. $\dfrac{d^2x}{dt^2} + 2\dfrac{dx}{dt} + x = 5e^{-2t} + t$

    $x(0) = 2;\ \dfrac{dx}{dt}(0) = 1$

    c. $\dfrac{d^2x}{dt^2} + 4x = t^2$

    $x(0) = 1;\ \dfrac{dx}{dt}(0) = 2$

PROGRESSIVE ANALYSIS AND DESIGN PROBLEMS

21. **High-speed rail pantograph.** Some high-speed rail systems are powered by electricity supplied to a pantograph on the train's roof from a catenary overhead, as shown in Figure P1.11. The force applied by the pantograph to the catenary is regulated to avoid loss of contact due to excessive transient motion. A proposed method to regulate the force uses a closed-loop feedback system, whereby a force, F_{up}, is applied to the bottom of the pantograph, resulting in an output
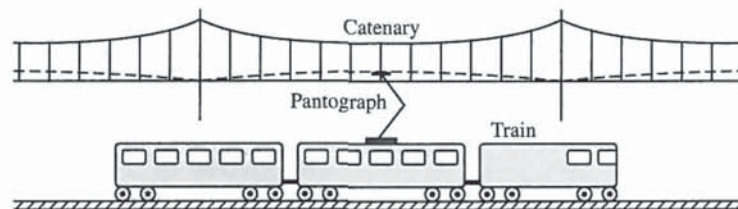

FIGURE P1.11   High-speed rail system showing pantograph and catenary (Reprinted with permission of ASME.)

force applied to the catenary at the top. The contact between the head of the pantograph and the catenary is represented by a spring. The output force is proportional to the displacement of this spring, which is the difference between the catenary and pantograph head vertical positions (*O'Connor, 1997*). Draw a functional block diagram showing the following signals: the desired output force as the input; the force, F_{up}, applied to the bottom of the pantograph; the difference in displacement between the catenary and pantograph head; and the output contact force. Also, show blocks representing the input transducer, controller, actuator generating F_{up}, pantograph dynamics, spring described above, and output sensor. All forces and displacements are measured from equilibrium.

22. **Contol of HIV/AIDS.** As of 2005, the number of people living worldwide with Human Immuno-deficiency Virus/Acquired Immune Deficiency Syndrome (HIV/AIDS) was estimated at 40 million, with 5 million new infections per year and 3 million deaths due to the disease (*UNAIDS, 2005*). Currently there is no known cure for the disease, and HIV cannot be completely eliminated in an infected individual. Drug combinations can be used to maintain the virus numbers at low levels, which helps prevent AIDS from developing. A common treatment for HIV is the administration of two types of drugs: reverse transcriptase inhibitors (RTIs) and protease inhibitors (PIs). The amount in which each of these drugs is administered is varied according to the amount of HIV viruses in the body (*Craig, 2004*). Draw a block diagram of a feedback system designed to control the amount of HIV viruses in an infected person. The plant input variables are the amount of RTIs and PIs dispensed. Show blocks representing the controller, the system under control, and the transducers. Label the corresponding variables at the input and output of every block.

23. **Hybrid vehicle.** The use of hybrid cars is becoming increasingly popular. A hybrid electric vehicle (HEV) combines electric machine(s) with an internal combustion engine (ICE), making it possible (along with other fuel consumption–reducing measures, such as stopping the ICE at traffic lights) to use smaller and more efficient gasoline engines. Thus, the efficiency advantages of the electric drivetrain are obtained, while the energy needed to power the electric motor is stored in the onboard fuel tank and not in a large and heavy battery pack.

There are various ways to arrange the flow of power in hybrid car. In a serial HEV (Figure P1.12), the ICE is not connected to the drive shaft. It drives only the generator, which charges the batteries and/ or supplies power to the electric motor(s) through an inverter or a converter.
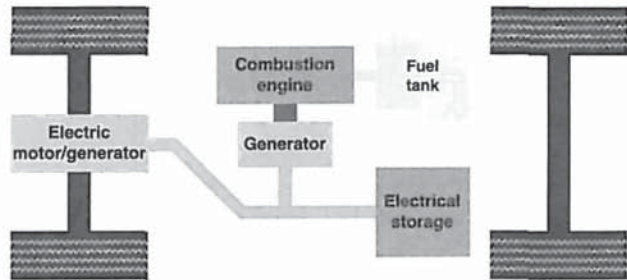

FIGURE P1.12   Serial hybrid-electric vehicle

The HEVs sold today are primarily of the parallel or split-power variety. If the combustion engine can turn the drive wheels as well as the generator, then the vehicle is referred to as a *parallel* hybrid, because both an electric motor and the ICE can drive the vehicle. A parallel hybrid car (Figure P1.13) includes a relatively small battery pack (electrical storage) to put out extra power to the electric motor when fast acceleration is needed. See (*Bosch 5th ed., 2000*), (*Bosch 7th ed., 2007*), (*Edelson, 2008*), (*Anderson, 2009*) for more detailed information about HEV.
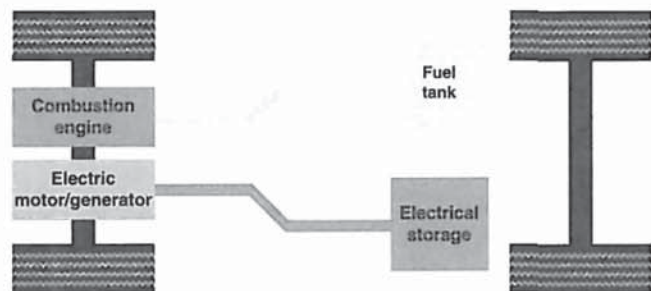
FIGURE P1.13   Parallel hybrid drive

As shown in Figure P1.14, split-power hybrid cars utilize a combination of series and parallel drives (*Bosch, 5th ed., 2007*). These cars use a planetary gear (3) as a split-power transmission to allow some of the ICE power to be applied mechanically to the drive. The other part is converted into electrical energy through the alternator (7) and the inverter (5) to feed the electric motor (downstream of the transmission) and/or to charge the high-voltage

battery (6). Depending upon driving conditions, the ICE, the electric motor, or both propel the vehicle.

1. internal-combustion engine; 2. tank
3. planetary gear; 4. electric motor; 5. inverter;
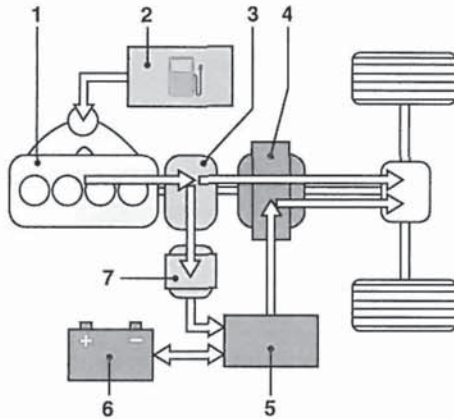*6. battery; 7. alternator.*

FIGURE P1.14   Split-power hybrid electric vehicle

Draw a functional block diagram for the cruise (speed) control system of:

a. A serial hybrid vehicle, showing its major components, including the speed sensor, electronic control unit (ECU), inverter, electric motor, and vehicle dynamics; as well as all signals, including the desired vehicle speed, actual speed, control command (ECU output), controlled voltage (inverter output), the motive force (provided by the electric motor), and running resistive force[7];

b. A parallel hybrid vehicle, showing its major components, which should include also a block that represents the accelerator, engine, and motor, as well as the signals (including accelerator displacement and combined engine/motor motive force);

c. A split-power HEV, showing its major components and signals, including, in addition to those listed in Parts **a** and **b**, a block representing the planetary gear and its control, which, depending upon driving conditions, would allow the ICE, the electric motor, or both to propel the vehicle, that is, to provide the necessary total motive force.

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[7] These include the aerodynamic drag, rolling resistance, and climbing resistance. The aerodynamic drag is a function of car speed, whereas the other two are proportional to car weight.

Cyber Exploration Laboratory

Experiment 1.1

Objective   To verify the behavior of closed-loop systems as described in the Chapter 1 Case Study.

Minimum Required Software Packages   LabVIEW and the LabVIEW Control Design and Simulation Module. *Note*: While no knowledge of LabVIEW is required for this experiment, see Appendix D to learn more about LabVIEW, which will be pursued in more detail in later chapters.

Prelab

1. From the discussion in the Case Study, describe the effect of the gain of a closed-loop system upon transient response.

2. From the discussion in the Case Study about steady-state error, sketch a graph of a step input superimposed with a step response output and show the steady-state error. Assume any transient response. Repeat for a ramp input and ramp output response. Describe the effect of gain upon the steady-state error.

Lab

1. Launch LabVIEW and open **Find Examples . . .**

2. In the **NI Example Finder** window, open **CDEx Effect of Controller Type.vi,** found by navigating to it thourgh **Toolkits and Modules/Control and Simulation/ Control Design/Time Analysis/CDEx Effect of Controller Type vi.**

3. On the tool bar click the circulating arrows located next to the solid arrow on the left. The program is now running.

4. Move the slider **Controller Gain** and note the effect of high and low gains.

5. Change the controller by clicking the arrows for **Controller Type** and repeat Step 4.

Postlab

1. Correlate the responses found in the experiment with those described in your Prelab. *Explore other examples provided in the LabVIEW example folders.*

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