

Norman S. Nise

CONTROL SYSTEMS ENGINEERING

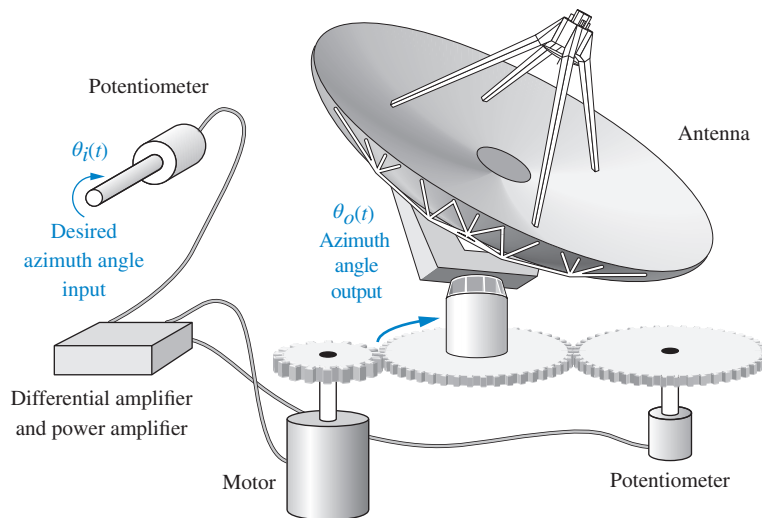
Seventh Edition



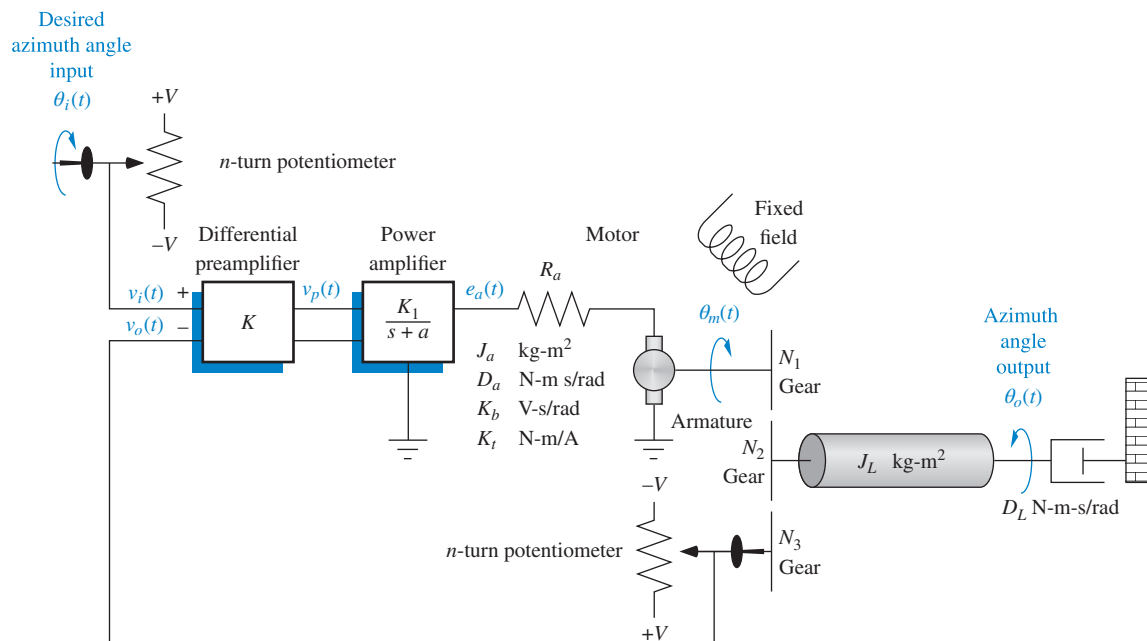
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Antenna Azimuth Position Control System

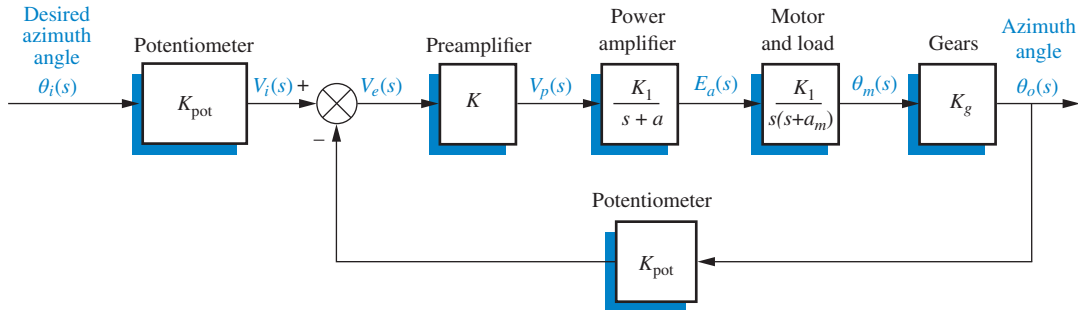
Layout



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

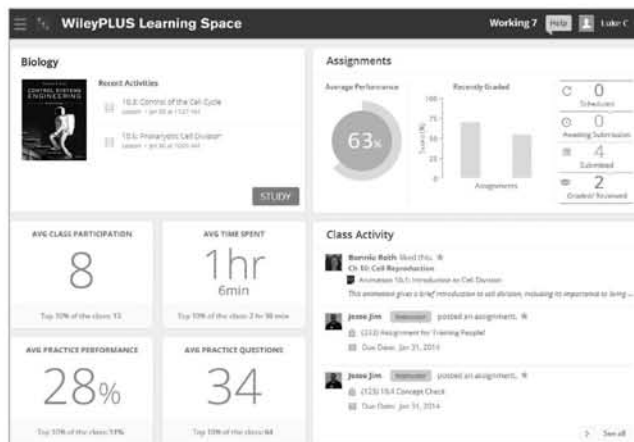
Block Diagram Parameters

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.

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CONTROL SYSTEMS ENGINEERING

Seventh Edition

Norman S. Nise

California State Polytechnic University, Pomona

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

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The new Honda robot ASIMO walks up stairs during a North American educational tour designed to introduce the public to ASIMO and to encourage students to study robotics science. ASIMO (Advanced Step in Innovative Mobility) is a product of over 15 years of robotic development at Honda and was created for the purpose of helping people in need. (Photo by Spencer Platt/Getty Images). This book has not been approved, licensed, or sponsored by Honda.

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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 seventh edition are:

- Standardized chapter organization
- Qualitative and quantitative explanations
- **Examples, Skill-Assessment Exercises, and Case Studies** throughout the text
- **Cyber Exploration Laboratory, Hardware Interface 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}
- Icons identifying major topics

Let us look at each feature in more detail.

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

² LabVIEW is a registered trademark of National Instruments Corporation.

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 are 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 Unmanned Free-Swimming Submersible Vehicle, is developed over the course of five chapters.

Cyber Exploration Laboratory, Hardware Interface 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**. 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.

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

Subsequent to the Cyber Exploration Laboratory experiments, and new to this seventh edition, are Hardware Interface Laboratory experiments in some chapters. These experiments use National Instruments' myDAQ to interface your computer to actual hardware to test control system principles in the real world.

Finally, in this seventh edition are Virtual Experiments. These experiments are more tightly focused than the Cyber Exploration Laboratory experiments as they let students interact with virtual models of actual teaching lab equipment produced by Quanser. These experiments will help students gain a more intuitive understanding of the physical implications of important control concepts. The experiments are referenced in sidebars throughout some chapters.

Abundant Illustrations

The ability to visualize concepts and processes is critical to the student's understanding. 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

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 identified 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**. Design Problems also can be found 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.

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 state-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 seventh edition, MATLAB and LabVIEW continue to be integrated into the text as an optional feature.

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

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

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 LTI Viewer, and the SISO Design Tool, is provided as an enhancement and is not required to use the text.

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.

MATLAB

ML

Simulink

SL

GUI Tool

GUIT

Symbolic Math

SM

LabVIEW

LV

State Space

SS

Design

D

New to This Edition

The following list describes the key changes in this seventh 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 solar energy parabolic trough collector.

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 seventh edition. The MATLAB tutorial has been updated to MATLAB Version 8.3 (R2014a), the Control System Toolbox Version 9.7, and the Symbolic Math Toolbox Version 6.0

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

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 seventh edition. We also continue to use Simulink to demonstrate how to simulate digital systems. Finally, the Simulink tutorial has

been updated to Simulink 8.3 and a new section has been added: **Using Simulink for Control System Design**.

LabVIEW

LabVIEW continues to be integrated in problems and experiments. LabVIEW has been updated to LabVIEW 2013.

Hardware Interface Laboratory

New to this edition are experiments that use National Instruments' myDAQ to control an actual motor. A tutorial to familiarize the reader with myDAQ is added to Appendix D LabVIEW Tutorial.

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

The BCS for the seventh 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
- LabVIEW VIs used in Appendix D
- All files required to perform Hardware Interface Laboratory experiments using National Instruments myDAQ

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 to 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

⁴PowerPoint is a registered trademark of Microsoft Corporation.

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.

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.

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I am deeply indebted to my colleagues, Drs. Elhami T. Ibrahim and Salomon Oldak at California State Polytechnic University, Pomona for authoring the creative new problems you will find at the end of every chapter. The new progressive problem, solar energy parabolic trough collector, that is at the end of every chapter is the creation of Dr. Oldak. In addition, I am grateful to Dr. Oldak for creating the National Instruments myDAQ experiments, which you will find in the Hardware Interface Laboratory section of many chapters. Finally, I want to thank Dr. Norali Pernaleté, also of California State Polytechnic University, Pomona, for her contribution of the LabVIEW experiments and problems continuing in this edition.

I would like to express my appreciation to those who participated in reviews of this seventh edition. They are: James R. McCusker, Wentworth Institute of Technology, and Ji-chul Ryu, Northern Illinois University.

The author would like to thank John Wiley & Sons, Inc. and its staff for once again providing professional support for this project through all phases of its development. Specifically, the following are due recognition for their contributions: Don Fowley, Vice President and Publisher, who gave full corporate support to the project; Dan Sayre, Executive Editor, with whom I worked closely and who provided guidance and leadership throughout the development of the seventh edition; Francesca Baratta and Jessica Knecht, Editorial Assistants who were always there to answer my questions and respond to my concerns in a professional manner; and Anna Melhorn, Senior Production Editor, who turned the seventh edition manuscript into the final product you are holding in your hands. Other contributors who worked hard behind the scenes are: Wendy Lai, Designer;

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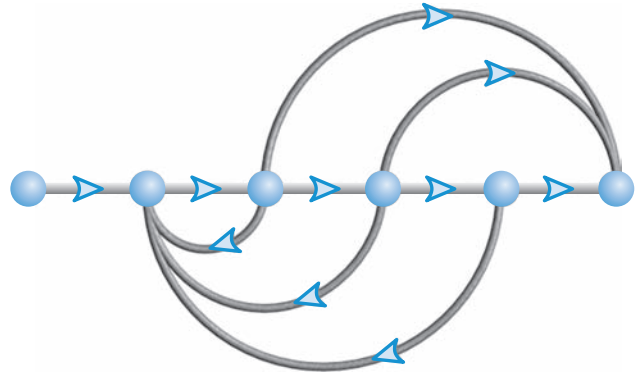
My sincere appreciation is extended to Erik Luther of National Instruments Corporation and Paul Gilbert, Michel Levis, and Tom Lee of Quanser for conceiving, coordinating, and developing the Virtual Experiments that I am sure will enhance your understanding of control systems. Others from National Instruments who contributed to the successful publication of this book are Margaret Barrett and Kathy Brown.

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 all editions. Specifically, though, thanks to her proofing pages for this seventh 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

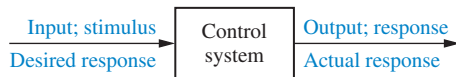


FIGURE 1.1 Simplified description of a control system

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.

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 level properly.

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

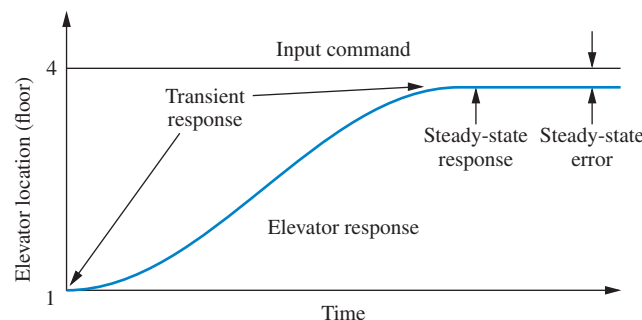
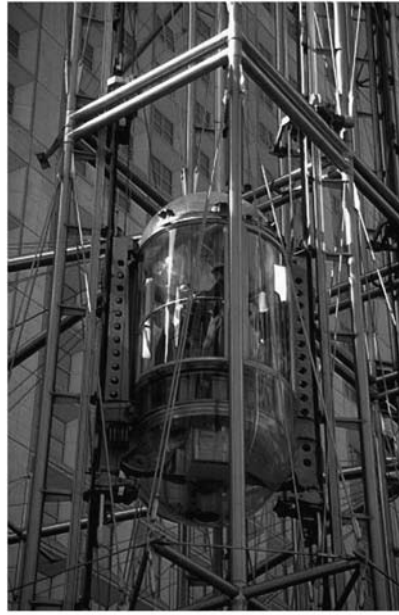


FIGURE 1.2 Elevator response



Bettman/Corbis. Courtesy of United Technologies Otis Elevator.



Art on File/Corbis

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; **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.

(a)

(b)

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:

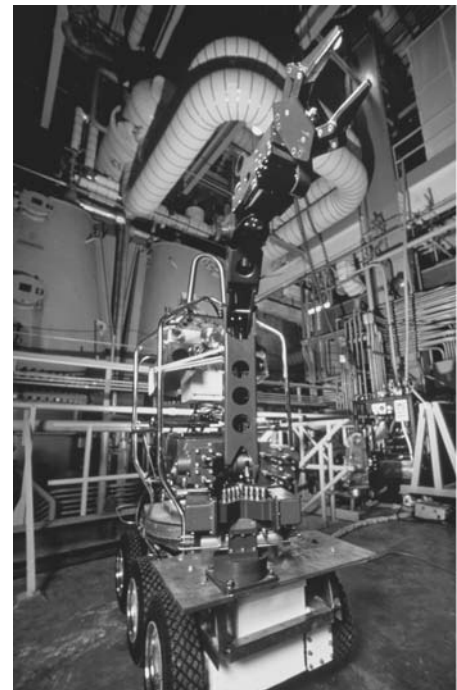
1. Power amplification
2. Remote control
3. Convenience of input form
4. Compensation for disturbances

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 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.



Hank Mogan/Science Source

FIGURE 1.4 Rover was built to work in contaminated areas at Three Mile Island in Middletown, Pennsylvania, where a nuclear accident occurred in 1979. The remote-controlled robot's long arm can be seen at the front of the vehicle.

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 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.

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

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.

Although recently retired, the space shuttle provides an excellent example of the use of control systems because it contained 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 used data from the shuttle's hardware to estimate vehicle position and velocity. This information was fed to the guidance equations that calculated commands for the shuttle's flight control systems, which steered the spacecraft. In space, the flight control system gimballed (rotated) the orbital maneuvering system (OMS) engines into a position that provided thrust in the commanded direction to steer the spacecraft. Within the earth's atmosphere, the shuttle was 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 were numerous subsystems to control the vehicle's functions. For example, the elevons required a control system to ensure that their position was 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 required a similar control system to ensure that the rotating engine can accomplish its function with speed and accuracy. Control systems were also used to control and stabilize the vehicle during its descent from orbit. Numerous small jets that compose the reaction control system (RCS) were used initially in the exoatmosphere, where the aerosurfaces are ineffective. Control was passed to the aerosurfaces as the orbiter descended into the atmosphere.

Inside the shuttle, numerous control systems were required for power and life support. For example, the orbiter had three fuel-cell power plants that converted hydrogen and oxygen (reactants) into electricity and water for use by the crew. The fuel cells involved the use of control systems to regulate temperature and pressure. The reactant tanks were kept at constant pressure as the quantity of reactant diminishes. Sensors in the tanks sent 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.

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. 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.

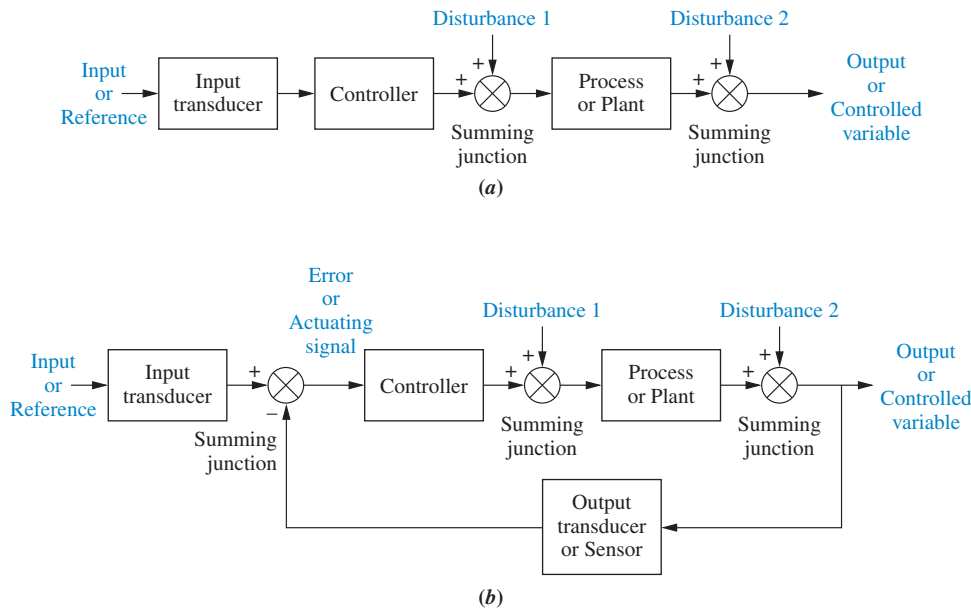


FIGURE 1.5 Block diagrams of control systems: **a.** open-loop system; **b.** closed-loop system

Open-Loop Systems

A generic *open-loop system* is shown in Figure 1.5(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 1.5(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 1.5(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 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 1.5(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 1.5(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 contained two digital computers, alone controlled numerous engine functions. It monitored engine sensors that provided pressures, temperatures, flow rates, turbopump speed, valve positions, and engine servo valve actuator positions. The controller further provided 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 1.6). 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.



Donald Swartz/Stockphoto

FIGURE 1.6 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.