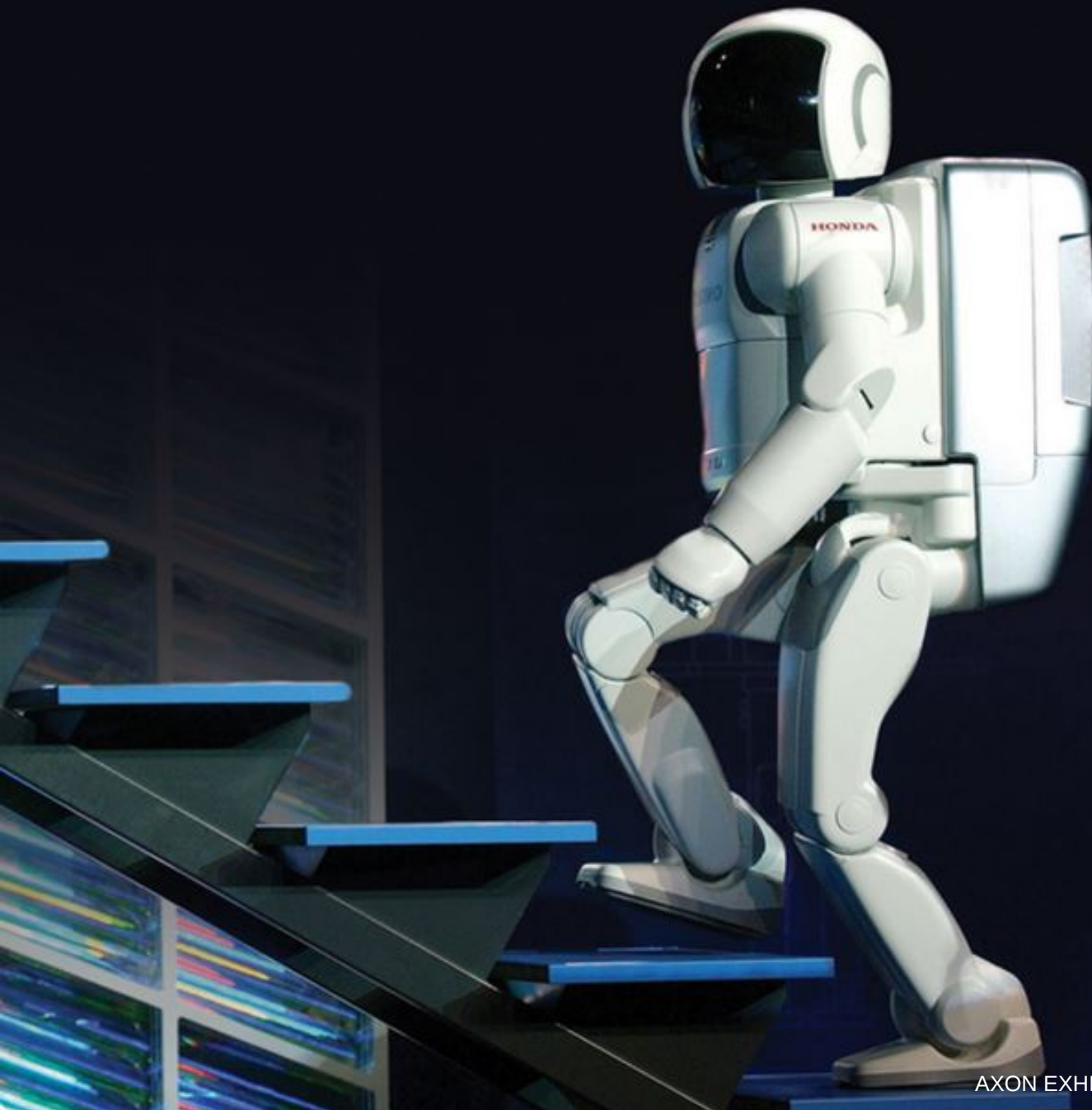


Norman S. Nise

CONTROL SYSTEMS ENGINEERING

Seventh Edition



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WILEY

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

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This book was set in 10/12 pt Lato Black by Thomson Digital and printed and bound by Courier Kendallville. The cover was printed by Courier Kendallville.

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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Library of Congress Cataloging-in-Publication Data

Nise, Norman S.
Control systems engineering / Norman S. Nise, California State Polytechnic University, Pomona. — Seventh edition.
1 online resource.
Includes bibliographical references and index.
Description based on print version record and CIP data provided by publisher; resource not viewed.
ISBN 978-1-118-80082-9 (pdf) — ISBN 978-1-118-17051-9 (cloth : alk. paper)
1. Automatic control—Textbooks. 2. Systems engineering—Textbooks. I. Title.
TJ213
629.8—dc23

2014037468

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

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.

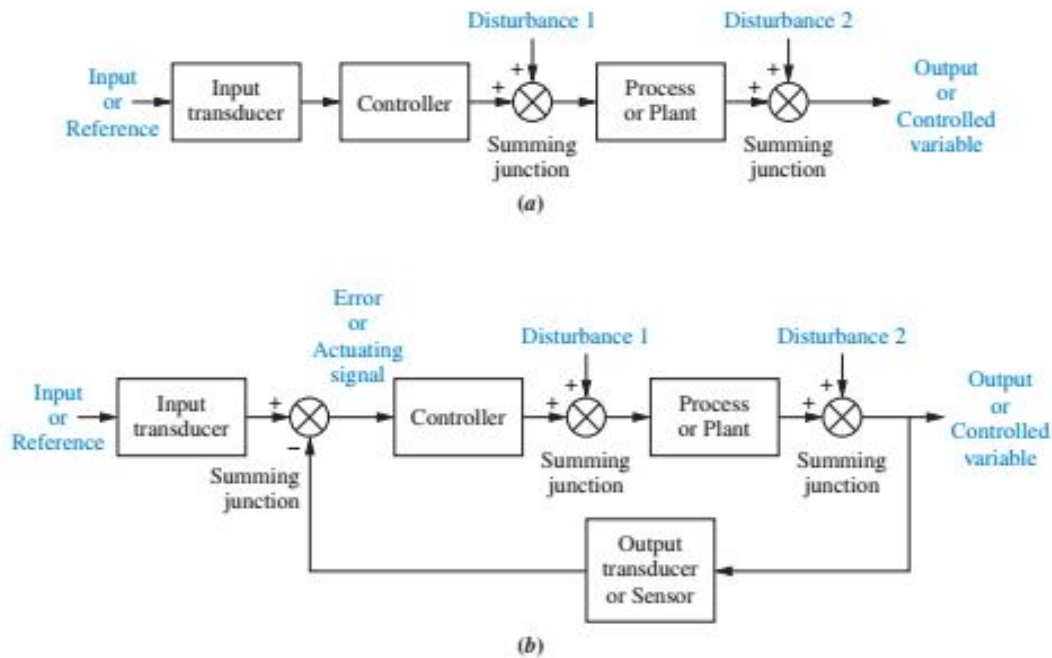


FIGURE 1.5 Block diagrams of control systems: a. open-loop system; b. closed-loop system

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.

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 1.7 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 1.8(a), with a more detailed layout and schematic in Figures 1.8(b) and 1.8(c), respectively. Figure 1.8(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 1.8 are repeated on the front endpapers for future reference.

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 1.8(d) and describe how this system works. The input command is an angular displacement. The potentiometer converts the angular displacement into a voltage. Similarly, the output angular displacement is converted to a voltage by the potentiometer 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.



Peter Menzel

FIGURE 1.7 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

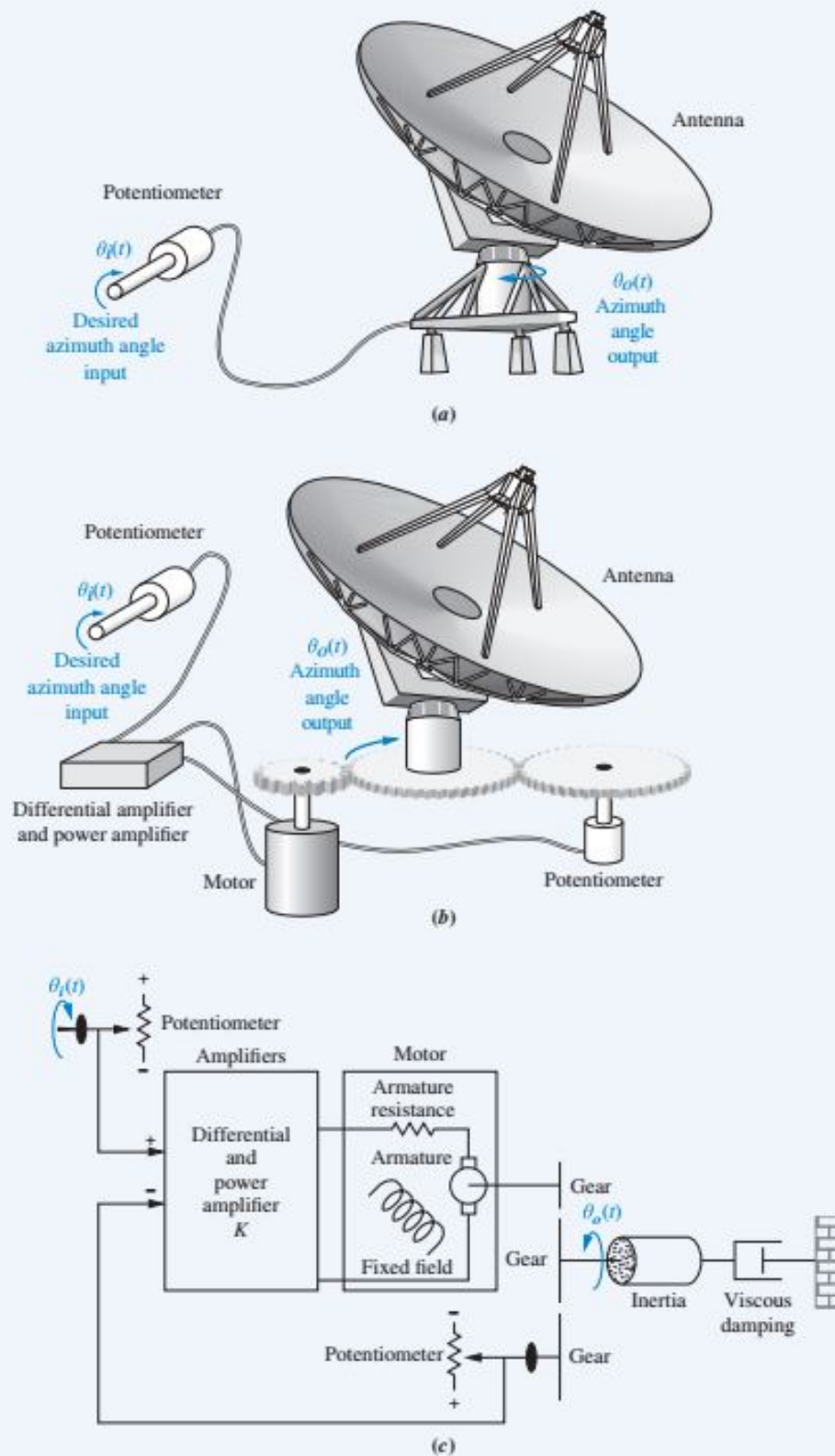


FIGURE 1.8 Antenna azimuth position control system: **a.** system concept; **b.** detailed layout; **c.** schematic (figure continues)

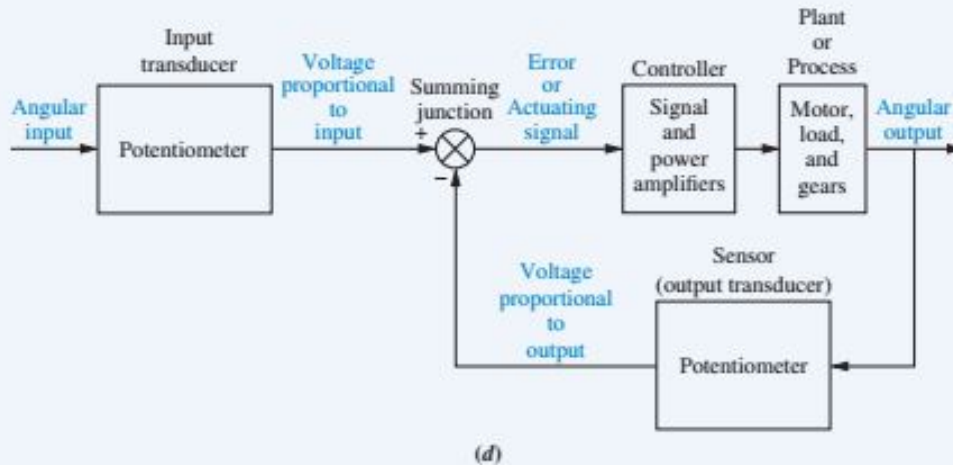


FIGURE 1.8 (Continued)
d. functional block diagram

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 1.9.

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 1.9 shows zero error in the steady-state response; that is, after the transients have disappeared, the output position

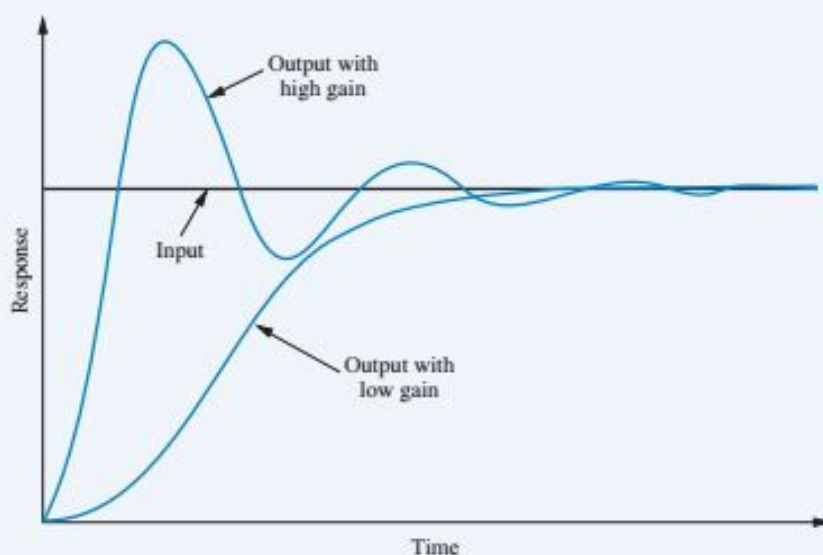


FIGURE 1.9 Response of a position control system, showing effect of high and low controller gain on the output response

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. An animation PowerPoint presentation (PPT) demonstrating this system is available for instructors. See *Antenna (Ch. 1)*.

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 1.10 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 Figure 1.10 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 1.10.

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

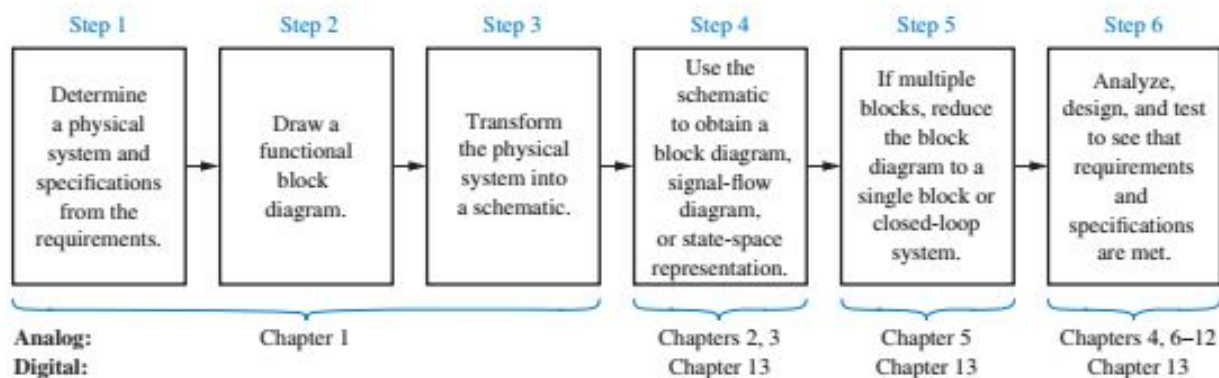


FIGURE 1.10 The control system design process