



10TH ... EDITION

AUTOMATIC CONTROL SYSTEMS

FARID GOLNARAGHI

BENJAMIN C. KUO

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Automatic Control Systems

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Simon Fraser University

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University of Illinois at Urbana-Champaign

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*To my wife, Mitra, and my daughters, Sophia and Carmen,
the joys of my life.*

FG

About the Authors

Dr. Farid Golnaraghi has been a professor and the Director of Mechatronic Systems Engineering at Simon Fraser University in Vancouver since 2006. He also holds a Burnaby Mountain Endowed Chair at SFU, and his primary research focuses on intelligent vehicle systems. Prior to joining SFU, Dr. Golnaraghi was a professor of Mechanical and Mechatronics Engineering at the University of Waterloo. His pioneering research has resulted in two textbooks, more than 150 journal and conference papers, four patents, and two start-up companies.

Dr. Benjamin C. Kuo was a member of the faculty of the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign, which he joined in 1958 upon the completion of his Ph.D. and where he remained for 31 rewarding years. He was a true visionary pioneer in the field of automatic control, and the impact of his distinguished career as a researcher and educator cannot be overstated.

In Memory of Professor Benjamin C. Kuo— A Visionary Pioneer and a Brilliant Teacher

When people think of an academic institution, it is its people—their intellect, their brilliance, and their impact—that defines it in their mind. The late Professor Benjamin Kuo is one of those brilliant professors who defines the University of Illinois, and, in particular, the Department of Electrical and Computer Engineering.

Ben was both an alumnus and a member of the faculty of the Department of Electrical and Computer Engineering at the University of Illinois. Upon the completion of his Ph.D., in 1958, he joined the faculty of the department and served it for 31 years through a stellar and most-influential career.

Ben was a visionary pioneer in the field of automatic control. His book *Automatic Control Systems*, which was first published in 1962, has been translated into many languages, and through nine editions over almost 50 years became one of the most widely read books in the field.

His symposium on Incremental Motion Control Systems and Devices, which was first held in 1972, became a pole of attraction for researchers and engineers from industry and academia from all over the world and contributed to the advancement of the field in a singular and most-influential manner.

The impact of Ben's distinguished career as a researcher and an educator is best described in terms of the ways he touched the lives of people:

- The over 120 graduate students who did their research under Ben's advising and mentorship, and who launched exciting careers in industry and academia and spread the new ideas of digital control and contributed to the growth of the field.
- The hundreds of thousands of students around the world who, through Ben's book, were introduced to the subject of automatic control and got excited about its multifaceted applications. I was one of them as an undergraduate student in Greece.
- And, finally, the billions of people all over the globe whose lives are easier and safer today thanks to the ubiquitous control electronics that Professor Benjamin Kuo dreamed about in the fertile grounds of the University of Illinois several decades ago.

The contributions of a brilliant mind endure long after the person passes and is no longer there.

*Andreas C. Cangellaris
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Preface

This tenth edition is with a new publisher, McGraw-Hill Education. It represents a complete overhaul of the textbook, which delivers practical coverage designed to introduce readers to the essential concepts of automatic control systems. The new edition features significant enhancements of all chapters, a greater number of solved examples, labs using both LEGO® MINDSTORMS® and MATLAB®/SIMLab, and a valuable introduction to the concept of Control Lab. The book gives students a real-world understanding of the subject and prepares them for the challenges they will one day face.

For this edition, we increased the number of examples, added more MATLAB toolboxes, and enhanced the MATLAB GUI software, **ACSYS**, to allow interface with LEGO MINDSTORMS. We also added more computer-aided tools for students and teachers. The new edition has been 5 years in the making, and was reviewed by many professors to better fine-tune the new concepts. In this edition, Chaps. 1 through 3 are organized to contain all background material, while Chaps. 4 through 11 contain material directly related to the subject of control. The Control Lab material is presented in great detail in App. D.

The following appendices for this book can be found at www.mhprofessional.com/golnaraghi:

Appendix A: Elementary Matrix Theory and Algebra

Appendix B: Mathematical Foundations

Appendix C: Laplace Transform Table

Appendix D: Control Lab

Appendix E: **ACSYS** 2013: Description of the Software

Appendix F: Properties and Construction of the Root Loci

Appendix G: General Nyquist Criterion

Appendix H: Discrete-Data Control Systems

Appendix I: Difference Equations

Appendix J: z -Transform Table

The following paragraphs are aimed at three groups: professors who have adopted the book or who we hope will select it as their text; practicing engineers looking for answers to solve their day-to-day design problems; and, finally, students who are going to live with the book because it has been assigned for the control-systems course they are taking.

To Professors

The material assembled in this book is an outgrowth of junior- and senior-level control-systems courses taught by Professors Golnaraghi and Kuo at their respective universities throughout their teaching careers. The first nine editions have been adopted by hundreds of universities in the United States and around the world and have been translated into at least six languages.

Most undergraduate control courses have labs dealing with time response and control of dc motors—namely, speed response, speed control, position response, and position control. In many cases, because of the high cost of control lab equipment, student exposure

to test equipment is limited, and as a result, many students do not gain a practical insight into the subject. In this tenth edition, recognizing these limitations, we introduce the concept of **Control Lab**, which includes two classes of experiments: **SIMLab (model-based simulation)** and **LEGOLab (physical experiments)**. These experiments are intended to supplement, or replace, the experimental exposure of the students in a traditional undergraduate control course.

In this edition, we have created a series of inexpensive control experiments for the **LEGO MINDSTORMS NXT** dc motor that will allow students to do their work within the **MATLAB** and **Simulink**[®] environment—even at home. See App. D for more details. This cost-effective approach may allow educational institutions to equip their labs with a number of LEGO test beds and maximize student access to the equipment at a fraction of the cost of currently available control-systems experiments. Alternatively, as a supplemental learning tool, students can take the equipment home after leaving a deposit and learn at their own pace. This concept has proven to be extremely successful at Simon Fraser University, Professor Golnaraghi's home university in Vancouver, Canada.

The labs include experiments on **speed and position control** of dc motors, followed by a **controller design project** involving control of a simple robotic system conducting a pick-and-place operation and position control of an elevator system. Two other projects also appear in Chaps. 6 and 7. The specific goals of these new experiments are

- To provide an in-depth, practical discussion of the dc motor speed response, speed control, and position control concepts.
- To provide examples on how to identify the parameters of a physical system, experimentally.
- To give a better feel for controller design through realistic examples.

This text contains not only conventional MATLAB toolboxes, where students can learn MATLAB and utilize their programming skills, but also a graphical MATLAB-based software, **ACSYS**. The **ACSYS** software added to this edition is very different from the software accompanying any other control book. Here, through extensive use of MATLAB GUI programming, we have created software that is easy to use. As a result, students need only to focus on learning control problems, not programming!

To Practicing Engineers

This book was written with the readers in mind and is very suitable for self-study. Our objective was to treat subjects clearly and thoroughly. The book does not use the theorem-proof–Q.E.D. style and is without heavy mathematics. We have consulted extensively for wide sectors of the industry for many years and have participated in solving numerous control-systems problems, from aerospace systems to industrial controls, automotive controls, and control of computer peripherals. Although it is difficult to adopt all the details and realism of practical problems in a textbook at this level, some examples and problems reflect simplified versions of real-life systems.

To Students

You have had it now that you have signed up for this course and your professor has assigned this book! You had no say about the choice, though you can form and express your opinion on the book after reading it. Worse yet, one of the reasons that your professor made the selection is because he or she intends to make you work hard. But please don't misunderstand us: What we really mean is that, though this is an easy book to study (in our opinion), it is a no-nonsense book. It doesn't have cartoons or nice-looking photographs to amuse you. From here on, it is all business and hard work. You should have had the prerequisites

of subjects found in a typical linear-systems course, such as how to solve linear ordinary differential equations, Laplace transforms and applications, and time-response and frequency-domain analysis of linear systems. In this book, you will not find too much new mathematics to which you have not been exposed before. What is interesting and challenging is that you are going to learn how to apply some of the mathematics that you have acquired during the past 2 or 3 years of study in college. In case you need to review some of the mathematical foundations, you can find them in the appendices, at www.mhprofessional.com/golnaraghi. You will also find the Simulink-based SIMLab and LEGOLab, which will help you to gain understanding of real-world control systems.

This book has numerous illustrative examples. Some of these are deliberately simple for the purpose of showing new ideas and subject matter. Some examples are more elaborate, in order to bring the practical world closer to you. Furthermore, the objective of this book is to present a complex subject in a clear and thorough way. One of the important learning strategies for you as a student is not to rely strictly on the textbook assigned. When studying a certain subject, go to the library and check out a few similar texts to see how other authors treat the same subject. You may gain new perspectives on the subject and discover that one author treats the material with more care and thoroughness than the others. Do not be distracted by written-down coverage with oversimplified examples. The minute you step into the real world, you will face the design of control systems with nonlinearities and/or time-varying elements as well as orders that can boggle your mind. You may find it discouraging to be told now that strictly linear and first-order systems do not exist in the real world.

Special Acknowledgments

Farid Golnaraghi wishes to thank Robert L. Argentieri, Editorial Director, Engineering, International & Professional Group, McGraw-Hill Education, for his efforts and support in publishing this new edition. Special thanks go to the reviewers for their invaluable comments and suggestions; the prepublication reviews have had a great impact on this revision. More special thanks go to the many School of Mechatronic Systems Engineering at Simon Fraser University faculty, students, and research associates, and all contributing undergraduate co-op students.

Professor Golnaraghi is grateful to and recognizes the Kuo estate, particularly Lori Dillon, for their support of this project.

Finally, he wishes to thank the late Professor Benjamin Kuo for sharing the pleasure of writing this wonderful book, and for his teachings, patience, and support throughout this experience.

Farid Golnaraghi
Vancouver, British Columbia, Canada

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CHAPTER 1

Introduction to Control Systems

The main objectives of this chapter are

1. To define a control system.
2. To explain why control systems are important.
3. To introduce the basic components of a control system.
4. To give some examples of control-system applications.
5. To explain why feedback is incorporated into most control systems.
6. To introduce types of control systems.

Over the past five decades, control systems have assumed an increasingly important role in the development and advancement of modern civilization and technology. Practically every aspect of our day-to-day activities is affected by some type of control system. For instance, in the domestic domain, we need to regulate the temperature and humidity of homes and buildings for comfortable living. For transportation, various functionalities

Learning Outcomes

After successful completion of this chapter, you will be able to

1. Appreciate the role and importance of control systems in our daily lives.
2. Understand the basic components of a control system.
3. Understand the difference between the open-loop and closed-loop systems, and the role of feedback in a closed-loop control system.
4. Gain a practical sense of real life control problems, through the use of **LEGO® MINDSTORMS®**, **MATLAB®**, and **Simulink®**.

of the modern automobiles and airplanes involve control systems. Industrially, manufacturing processes contain numerous objectives for products that will satisfy the precision and cost-effectiveness requirements. A human being is capable of performing a wide range of tasks, including decision making. Some of these tasks, such as picking up objects and walking from one point to another, are commonly carried out in a routine fashion. Under certain conditions, some of these tasks are to be performed in the best possible way. For instance, an athlete running a 100-yd dash has the objective of running that distance in the shortest possible time. A marathon runner, on the other hand, not only must run the distance as quickly as possible, but, in doing so, he or she must also control the consumption of energy and devise the best strategy for the race. The means of achieving these “objectives” usually involve the use of control systems that implement certain control strategies.

Control systems are found in abundance in all sectors of industry, such as quality control of manufactured products, automatic assembly lines, machine-tool control,

space technology, computer control, transportation systems, power systems, robotics, microelectromechanical systems (MEMS), nanotechnology, and many others. Even the control of inventory and social and economic systems may be approached from the control system theory. More specifically, applications of control systems benefit many areas, including

Control systems abound in modern civilization.

- **Process control.** Enable automation and mass production in industrial setting.
- **Machine tools.** Improve precision and increase productivity.
- **Robotic systems.** Enable motion and speed control.
- **Transportation systems.** Various functionalities of the modern automobiles and airplanes involve control systems.
- **MEMS.** Enable the manufacturing of very small electromechanical devices such as microsensors and microactuators.
- **Lab-on-a-chip.** Enable functionality of several laboratory tasks on a single chip of only millimeters to a few square centimeters in size for medical diagnostics or environmental monitoring.
- **Biomechanical and biomedical.** Artificial muscles, drug delivery systems, and other assistive technologies.

1-1 BASIC COMPONENTS OF A CONTROL SYSTEM

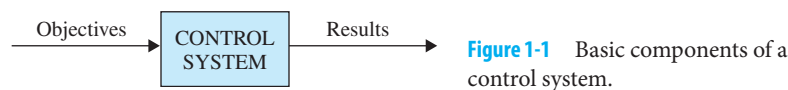
The basic ingredients of a control system can be described by

- Objectives of control.
- Control-system components.
- Results or outputs.

The basic relationship among these three components is illustrated in a block diagram representation, as shown Fig. 1-1. The **block diagram** representation, as later discussed in Chap. 4, provides a graphical approach to describe how components of a control system interact. In this case, the **objectives** can be identified with **inputs**, or **actuating signals**, u , and the results are also called **outputs**, or **controlled variables**, y . In general, the objective of the control system is to control the outputs in some prescribed manner by the inputs through the elements of the control system.

1-2 EXAMPLES OF CONTROL-SYSTEM APPLICATIONS

Applications of control systems have significantly increased through advances in computer technology and development of new materials, which provide unique opportunities for highly efficient actuation and sensing, thereby reducing energy losses and environmental impacts. State-of-the-art actuators and sensors may be implemented in virtually any system, including biological propulsion; locomotion; robotics; material handling; biomedical, surgical, and endoscopic; aeronautics; marine; and the defense and space industries.



The following represent some of the applications of control that have become part of our daily lives.

1-2-1 Intelligent Transportation Systems

The automobile and its evolution in the past two centuries is arguably the most transformative invention of man. Over the years, many innovations have made cars faster, stronger, and aesthetically appealing. We have grown to desire cars that are “intelligent” and provide maximum levels of comfort, safety, and fuel efficiency. Examples of intelligent systems in cars include climate control, cruise control, antilock brake systems (ABSs), active suspensions that reduce vehicle vibration over rough terrain, air springs that self-level the vehicle in high-G turns (in addition to providing a better ride), integrated vehicle dynamics that provide yaw control when the vehicle is either over- or understeering (by selectively activating the brakes to regain vehicle control), traction control systems to prevent spinning of wheels during acceleration, and active sway bars to provide “controlled” rolling of the vehicle. The following are a few examples.

Drive-by-Wire and Driver-Assist Systems

The new generations of intelligent vehicles are able to understand the driving environment, know their whereabouts, monitor their health, understand the road signs, and monitor driver performance, even overriding drivers to avoid catastrophic accidents. These tasks require significant overhaul of past designs. Drive-by-wire technology is replacing the traditional mechanical and hydraulic systems with electronics and control systems, using electromechanical actuators and human-machine interfaces such as pedal and steering feel emulators—otherwise known as haptic systems. Hence, the traditional components—such as the steering column, intermediate shafts, pumps, hoses, fluids, belts, coolers, brake boosters, and master cylinders—are eliminated from the vehicle. Haptic interfaces can offer adequate transparency to the driver while maintaining safety and stability of the system. Removing the bulky mechanical steering wheel column and the rest of the steering system has clear advantages in terms of mass reduction and safety in modern vehicles, along with improved ergonomics as a result of creating more driver space. Replacing the steering wheel with a haptic device that the driver controls through the sense of touch would be useful in this regard. The haptic device would produce the same sense to the driver as the mechanical steering wheel but with improvements in cost, safety, and fuel consumption as a result of eliminating the bulky mechanical system.

Driver-assist systems help drivers avoid or mitigate an accident by sensing the nature and significance of the danger. Depending on the significance and timing of the threat, these on-board safety systems will initially alert the driver as early as possible to an impending danger. Then, it will actively assist or, ultimately, intervene in order to avert the accident or mitigate its consequences. Provisions for automatic override features, when the driver loses control due to fatigue or lack of attention, will be an important part of the system. In such systems, the so-called advanced vehicle control system monitors the longitudinal and lateral control, and by interacting with a central management unit, it will be ready to take control of the vehicle whenever the need arises. The system can be readily integrated with sensor networks that monitor every aspect of the conditions on the road and are prepared to take appropriate action in a safe manner.

Integration and Utilization of Advanced Hybrid Powertrains

Hybrid technologies offer improved fuel consumption while enhancing driving experience. Utilizing new energy storage and conversion technologies and integrating them with powertrains are prime objectives in hybrid technologies. Such technologies must be

compatible with combustion engine platforms and must enhance, rather than compromise, vehicle function. Sample applications include plug-in hybrid technology, which would enhance the vehicle cruising distance based on using battery power alone, and utilizing fuel cells, energy harvesting (e.g., by converting the vibration energy in the suspension or the energy in the brakes into electrical energy) or sustainable energy resources, such as solar and wind power, to charge the batteries. The smart plug-in vehicle can be a part of an integrated smart home and grid energy system of the future, which would utilize smart energy metering devices for optimal use of grid energy by avoiding peak energy consumption hours.

High-Performance Real-Time Control, Health Monitoring, and Diagnosis

Modern vehicles utilize an increasing number of sensors, actuators, and networked embedded computers. The need for high-performance computing would increase with the introduction of such revolutionary features as drive-by-wire systems into modern vehicles. The tremendous computational burden of processing sensory data into appropriate control and monitoring signals and diagnostic information creates challenges in the design of embedded computing technology. Toward this end, a related challenge is to incorporate sophisticated computational techniques that control, monitor, and diagnose complex automotive systems while meeting requirements such as low power consumption and cost-effectiveness.

1-2-2 Steering Control of an Automobile

As a simple example of the control system, as shown in Fig. 1-1, consider the steering control of an automobile. The direction of the two front wheels can be regarded as the controlled variable, or the output, y ; the direction of the steering wheel is the actuating signal, or the input, u . The control system, or process in this case, is composed of the steering mechanism and the dynamics of the entire automobile. However, if the objective is to control the speed of the automobile, then the amount of pressure exerted on the accelerator is the actuating signal, and the vehicle speed is the controlled variable. As a whole, we can regard the simplified automobile control system as one with two inputs (steering and accelerator) and two outputs (heading and speed). In this case, the two controls and two outputs are independent of each other, but there are systems for which the controls are coupled. Systems with more than one input and one output are called **multivariable systems**.

1-2-3 Idle-Speed Control of an Automobile

As another example of a control system, we consider the idle-speed control of an automobile engine. The objective of such a control system is to maintain the engine idle speed at a relatively low value (for fuel economy) regardless of the applied engine loads (e.g., transmission, power steering, air conditioning). Without the idle-speed control, any sudden engine-load application would cause a drop in engine speed that might cause the engine to stall. Thus the main objectives of the idle-speed control system are (1) to eliminate or minimize the speed droop when engine loading is applied and (2) to maintain the engine idle speed at a desired value. Figure 1-2 shows the block diagram of the idle-speed control system from the standpoint of inputs–system–outputs. In this case, the throttle angle α and the load torque T_L (due to the application of air conditioning, power steering, transmission, or power brakes, etc.) are the inputs, and the engine speed ω is the output. The engine is the controlled process of the system.

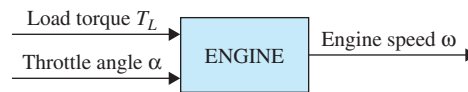
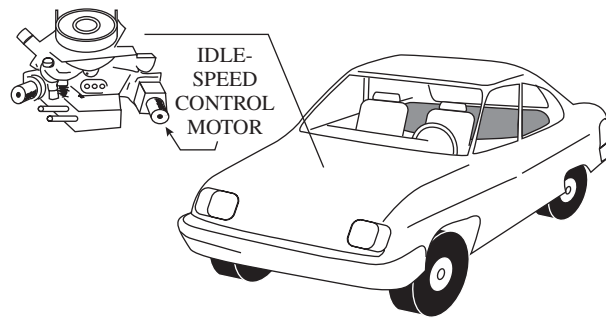


Figure 1-2 Idle-speed control system.



Figure 1-3 Solar collector field.¹

1-2-4 Sun-Tracking Control of Solar Collectors

To achieve the goal of developing economically feasible non-fossil-fuel electrical power, a great deal of effort has been placed on alternative energy including research and development of solar power conversion methods, including the solar-cell conversion techniques. In most of these systems, the need for high efficiencies dictates the use of devices for sun tracking. Figure 1-3 shows a solar collector field. Figure 1-4 shows a conceptual method of efficient water extraction using solar power. During the hours of daylight, the solar collector would produce electricity to pump water from the underground water table to a reservoir (perhaps on a nearby mountain or hill), and in the early morning hours, the water would be released into the irrigation system.

One of the most important features of the solar collector is that the collector dish must track the sun accurately. Therefore, the movement of the collector dish must be controlled

¹Source: <http://stateimpact.npr.org/texas/files/2011/08/Solar-Energy-Power-by-Daniel-Reese-01.jpg>.

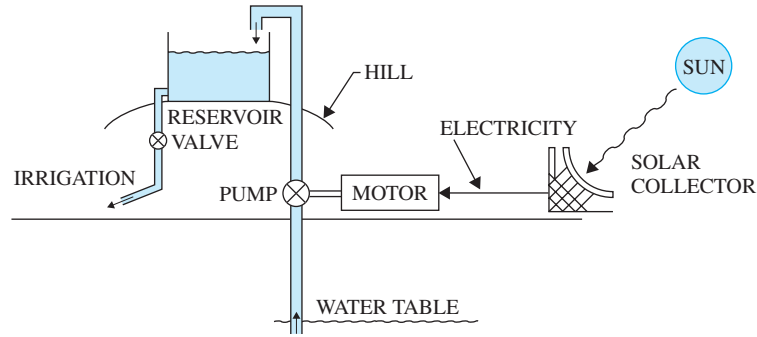


Figure 1-4 Conceptual method of efficient water extraction using solar power.

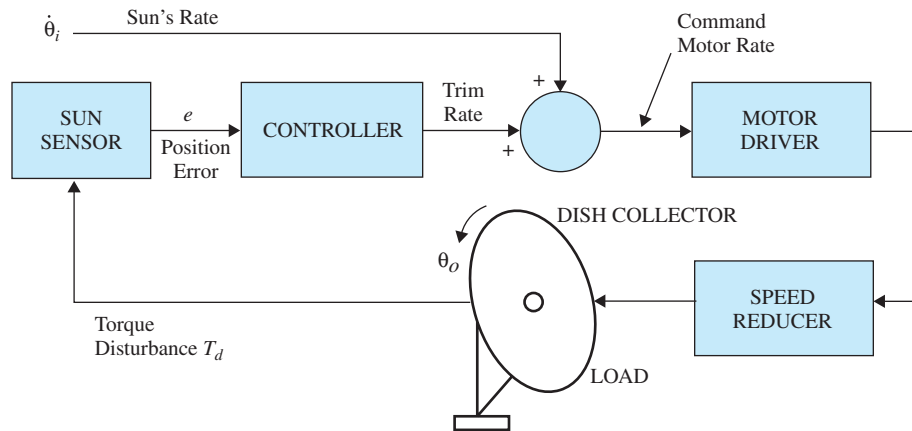


Figure 1-5 Important components of the sun-tracking control system.

by sophisticated control systems. The block diagram of Fig. 1-5 describes the general philosophy of the sun-tracking system together with some of the most important components. The controller ensures that the tracking collector is pointed toward the sun in the morning and sends a “start track” command. The controller constantly calculates the sun’s rate for the two axes (azimuth and elevation) of control during the day. The controller uses the sun rate and sun sensor information as inputs to generate proper motor commands to slew the collector.

1-3 OPEN-LOOP CONTROL SYSTEMS (NONFEEDBACK SYSTEMS)

The idle-speed control system illustrated in Fig. 1-2, shown previously, is rather unsophisticated and is called an **open-loop control system**. It is not difficult to see that the system as shown would not satisfactorily fulfill critical performance requirements. For instance, if the throttle angle α is set at a certain initial value that corresponds to a certain engine speed, then when a load torque T_L is applied, there is no way to prevent a drop in the engine speed. The only way to make the system work is to have a means of adjusting α in response to a change in the load torque in order to maintain ω at the desired level. The conventional electric washing machine is another example

Open-loop systems are economical but usually inaccurate.

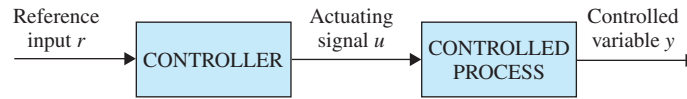


Figure 1-6 Elements of an open-loop control system.

of an open-loop control system because, typically, the amount of machine wash time is entirely determined by the judgment and estimation of the human operator.

The elements of an open-loop control system can usually be divided into two parts: the **controller** and the **controlled process**, as shown by the block diagram of Fig. 1-6. An input signal, or command, r , is applied to the controller, whose output acts as the actuating signal u ; the actuating signal then controls the controlled process so that the controlled variable y will perform according to some prescribed standards. In simple cases, the controller can be an amplifier, a mechanical linkage, a filter, or other control elements, depending on the nature of the system. In more sophisticated cases, the controller can be a computer such as a microprocessor. Because of the simplicity and economy of open-loop control systems, we find this type of system in many noncritical applications.

1-4 CLOSED-LOOP CONTROL SYSTEMS (FEEDBACK CONTROL SYSTEMS)

What is missing in the open-loop control system for more accurate and more adaptive control is a link or feedback from the output to the input of the system. To obtain more accurate control, the controlled signal y should be fed back and compared with the reference input, and an actuating signal proportional to the difference of the input and the output must be sent through the system to correct the error. A system with one or more feedback paths such as that just described is called a **closed-loop system**.

A closed-loop idle-speed control system is shown in Fig. 1-7. The reference input ω_r sets the desired idling speed. The engine speed at idle should agree with the reference value ω_r , and any difference such as the load torque T_L is sensed by the speed transducer and the error detector. The controller will operate on the difference and provide a signal to adjust the throttle angle α to correct the error. Figure 1-8 compares the typical performances of open-loop and closed-loop idle-speed control systems. In Fig. 1-8a, the idle speed of the open-loop system will drop and settle at a lower value after a load torque is applied. In Fig. 1-8b, the idle speed of the closed-loop system is shown to recover quickly to the preset value after the application of T_L .

Closed-loop systems have many advantages over open-loop systems.

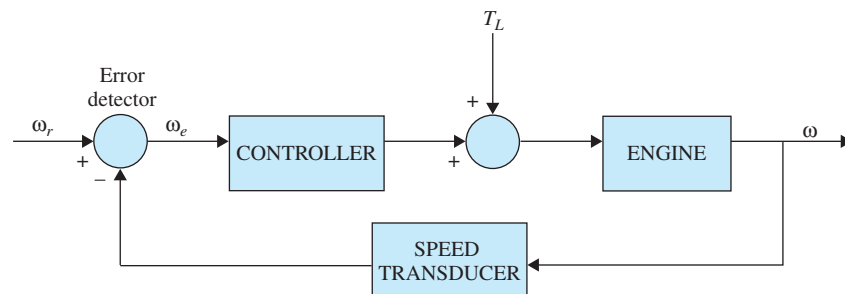


Figure 1-7 Block diagram of a closed-loop idle-speed control system.

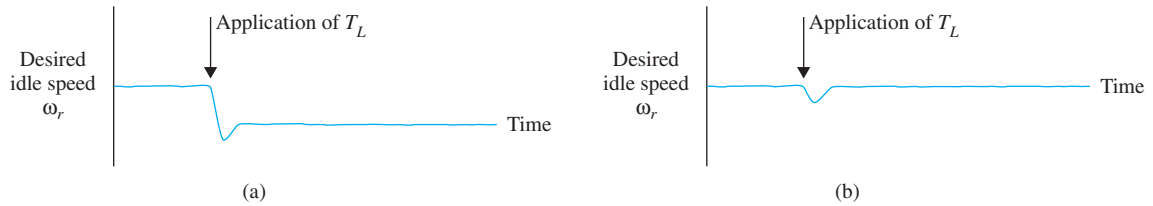


Figure 1-8 (a) Typical response of the open-loop idle-speed control system. (b) Typical response of the closed-loop idle-speed control system.

The objective of the idle-speed control system illustrated, also known as a **regulator system**, is to maintain the system output at a prescribed level.

1-5 WHAT IS FEEDBACK, AND WHAT ARE ITS EFFECTS?

The motivation for using feedback, as illustrated by the examples in Sec. 1-1, is somewhat oversimplified. In these examples, feedback is used to reduce the error between the reference input and the system output. However, the significance of the effects of feedback in control systems is more complex than is demonstrated by these simple examples. The reduction of system error is merely one of the many important effects that feedback may have upon a system. We show in the following sections that feedback also has effects on such system performance characteristics as **stability**, **bandwidth**, **overall gain**, **impedance**, and **sensitivity**.

To understand the effects of feedback on a control system, it is essential to examine this phenomenon in a broad sense. When feedback is deliberately introduced for the purpose of control, its existence is easily identified. However, there are numerous situations where a physical system that we recognize as an inherently nonfeedback system turns out to have feedback when it is observed in a certain manner. In general, we can state that whenever a closed sequence of **cause-and-effect relationships** exists among the variables of a system, feedback is said to exist. This viewpoint will inevitably admit feedback in a large number of systems that ordinarily would be identified as nonfeedback systems. However, control-system theory allows numerous systems, with or without physical feedback, to be studied in a systematic way once the existence of feedback in the sense mentioned previously is established.

We shall now investigate the effects of feedback on the various aspects of system performance. Without the necessary mathematical foundation of linear-system theory, at this point we can rely only on simple static-system notation for our discussion. Let us consider the simple feedback system configuration shown in Fig. 1-9, where r is the input signal; y , the output signal; e , the error; and b , the feedback signal. The parameters G and H

Feedback exists whenever there is a closed sequence of cause-and-effect relationships.

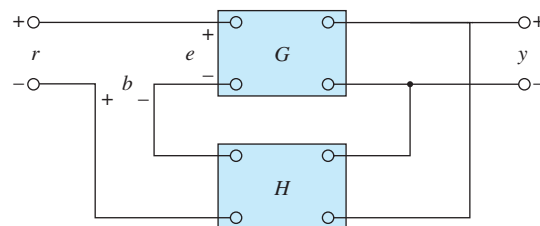


Figure 1-9 Feedback system.

may be considered as constant gains. By simple algebraic manipulations, it is simple to show that the input–output relation of the system is

$$M = \frac{y}{r} = \frac{G}{1 + GH} \quad (1-1)$$

Using this basic relationship of the feedback system structure, we can uncover some of the significant effects of feedback.

1-5-1 Effect of Feedback on Overall Gain

As seen from Eq. (1-1), feedback affects the gain G of a nonfeedback system by a factor of $1 + GH$. The system of Fig. 1-9 is said to have **negative feedback** because a minus sign is assigned to the feedback signal. The quantity GH may itself include a minus sign, so the *general effect of feedback is that it may increase or decrease the gain G* . In a practical control system, G and H are functions of frequency, so the magnitude of $1 + GH$ may be greater than 1 in one frequency range but less than 1 in another. Therefore, *feedback could increase the gain of system in one frequency range but decrease it in another*.

Feedback may increase the gain of a system in one frequency range but decrease it in another.

1-5-2 Effect of Feedback on Stability

Stability is a notion that describes whether the system will be able to follow the input command, that is, be useful in general. In a nonrigorous manner, *a system is said to be unstable if its output is out of control*. To investigate the effect of feedback on stability, we can again refer to the expression in Eq. (1-1). If $GH = -1$, the output of the system is infinite for any finite input, and the system is said to be unstable. Therefore, we may state that *feedback can cause a system that is originally stable to become unstable*. Certainly, feedback is a double-edged sword; when it is improperly used, it can be harmful. It should be pointed out, however, that we are only dealing with the static case here, and, in general, $GH = -1$ is not the only condition for instability. The subject of system stability will be treated formally in Chap. 5.

A system is unstable if its output is out of control.

It can be demonstrated that one of the advantages of incorporating feedback is that it can stabilize an unstable system. Let us assume that the feedback system in Fig. 1-9 is unstable because $GH = -1$. If we introduce another feedback loop through a negative feedback gain of F , as shown in Fig. 1-10, the input–output relation of the overall system is

$$\frac{y}{r} = \frac{G}{1 + GH + GF} \quad (1-2)$$

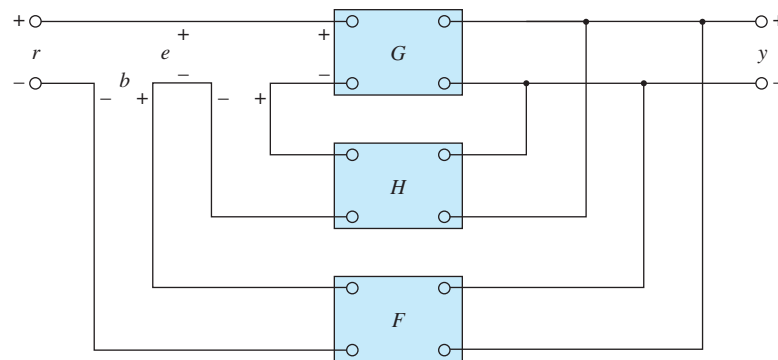


Figure 1-10 Feedback system with two feedback loops.

It is apparent that although the properties of G and H are such that the inner-loop feedback system is unstable because $GH = -1$, the overall system can be stable by properly selecting the outer-loop feedback gain F . In practice, GH is a function of frequency, and the stability condition of the closed-loop system depends on the **magnitude** and **phase** of GH . The bottom line is that *feedback can improve stability or be harmful to stability if it is not properly applied*.

Feedback can improve stability or be harmful to stability.

Sensitivity considerations often are important in the design of control systems. Because all physical elements have properties that change with environment and age, we cannot always consider the parameters of a control system to be completely stationary over the entire operating life of the system. For instance, the winding resistance of an electric motor changes as the temperature of the motor rises during operation. Control systems with electric components may not operate normally when first turned on because of the still-changing system parameters during warm-up. This phenomenon is sometimes called **morning sickness**. Most duplicating machines have a warm-up period during which time operation is blocked out when first turned on.

Note: Feedback can increase or decrease the sensitivity of a system.

In general, a good control system should be very insensitive to parameter variations but sensitive to the input commands. We shall investigate what effect feedback has on sensitivity to parameter variations. Referring to the system in Fig. 1-9, we consider G to be a gain parameter that may vary. The sensitivity of the gain of the overall system M to the variation in G is defined as

$$S_G^M = \frac{\partial M/G}{\partial G/M} = \frac{\text{percentage change in } M}{\text{percentage change in } G} \quad (1-3)$$

where ∂M denotes the incremental change in M due to the incremental change in G , or ∂G . By using Eq. (1-1), the sensitivity function is written

$$S_G^M = \frac{\partial M}{\partial G} \frac{G}{M} = \frac{1}{1+GH} \quad (1-4)$$

This relation shows that if GH is a positive constant, the magnitude of the sensitivity function can be made arbitrarily small by increasing GH , provided that the system remains stable. It is apparent that, in an open-loop system, the gain of the system will respond in a one-to-one fashion to the variation in G (i.e., $S_G^M = 1$). Again, in practice, GH is a function of frequency; the magnitude of $1 + GH$ may be less than unity over some frequency ranges, so feedback could be harmful to the sensitivity to parameter variations in certain cases. In general, the sensitivity of the system gain of a feedback system to parameter variations depends on where the parameter is located. The reader can derive the sensitivity of the system in Fig. 1-9 due to the variation of H .

1-5-3 Effect of Feedback on External Disturbance or Noise

All physical systems are subject to some types of extraneous signals or noise during operation. Examples of these signals are thermal-noise voltage in electronic circuits and brush or commutator noise in electric motors. External disturbances, such as wind gusts acting on an antenna, are also quite common in control systems. Therefore, control systems should be designed so that they are insensitive to noise and disturbances and sensitive to input commands.

Feedback can reduce the effect of noise.

The effect of feedback on noise and disturbance depends greatly on where these extraneous signals occur in the system. No general conclusions can be reached, but in many situations, *feedback can reduce the effect of noise and disturbance on system performance*. Let us refer to the system shown in Fig. 1-11, in which r denotes the command signal and

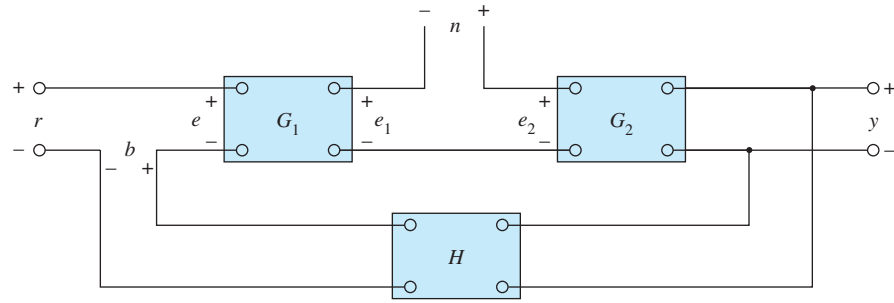


Figure 1-11 Feedback system with a noise signal.

n is the noise signal. In the absence of feedback, that is, $H = 0$, the output y due to n acting alone is

$$y = G_2 n \quad (1-5)$$

With the presence of feedback, the system output due to n acting alone is

$$y = \frac{G_2}{1 + G_1 G_2 H} n \quad (1-6)$$

Comparing Eq. (1-6) with Eq. (1-5) shows that the noise component in the output of Eq. (1-6) is reduced by the factor $1 + G_1 G_2 H$ if the latter is greater than unity and the system is kept stable.

In Chap. 11, the feedforward and forward controller configurations are used along with feedback to reduce the effects of disturbance and noise inputs. In general, feedback also has effects on such performance characteristics as bandwidth, impedance, transient response, and frequency response. These effects will be explained as we continue.

Feedback also can affect bandwidth, impedance, transient responses, and frequency responses.

1-6 TYPES OF FEEDBACK CONTROL SYSTEMS

Feedback control systems may be classified in a number of ways, depending upon the purpose of the classification. For instance, according to the method of analysis and design, control systems are classified as **linear** or **nonlinear**, and **time-varying** or **time-invariant**. According to the types of signal found in the system, reference is often made to **continuous-data** or **discrete-data** systems, and **modulated** or **unmodulated** systems. Control systems are often classified according to the main purpose of the system. For instance, a **position-control system** and a **velocity-control system** control the output variables just as the names imply. In Chap. 11, the **type** of control system is defined according to the form of the open-loop transfer function. In general, there are many other ways of identifying control systems according to some special features of the system. It is important to know some of the more common ways of classifying control systems before embarking on the analysis and design of these systems.

Most real-life control systems have nonlinear characteristics to some extent.

1-7 LINEAR VERSUS NONLINEAR CONTROL SYSTEMS

This classification is made according to the methods of analysis and design. Strictly speaking, linear systems do not exist in practice because all physical systems are nonlinear to some extent. Linear feedback control systems are idealized models fabricated by the analyst purely

for the simplicity of analysis and design. When the magnitudes of signals in a control system are limited to ranges in which system components exhibit linear characteristics (i.e., the principle of superposition applies), the system is essentially linear. But when the magnitudes of signals are extended beyond the range of the linear operation, depending on the severity of the nonlinearity, the system should no longer be considered linear. For instance, ampli-

There are no general methods for solving a wide class of nonlinear systems.

fiers used in control systems often exhibit a saturation effect when their input signals become large; the magnetic field of a motor usually has saturation properties. Other common nonlinear effects found in control systems are the backlash or dead play between coupled gear members, nonlinear spring characteristics, nonlinear friction force or torque between moving members, and so on. Quite often, nonlinear characteristics are intentionally introduced in a control system to improve its performance or provide more effective control. For instance, to achieve minimum-time control, an on-off-type (bang-bang or relay) controller is used in many missile or spacecraft control systems. Typically in these systems, jets are mounted on the sides of the vehicle to provide reaction torque for attitude control. These jets are often controlled in a full-on or full-off fashion, so a fixed amount of air is applied from a given jet for a certain time period to control the attitude of the space vehicle.

For linear systems, a wealth of analytical and graphical techniques is available for design and analysis purposes. A majority of the material in this text is devoted to the analysis and design of linear systems. Nonlinear systems, on the other hand, are usually difficult to treat mathematically, and there are no general methods available for solving a wide class of nonlinear systems. It is practical to first design the controller based on the linear-system model by neglecting the nonlinearities of the system. The designed controller is then applied to the nonlinear system model for evaluation or redesign by computer simulation. The Control Lab introduced in Chap. 8 may be used to model the characteristics of practical systems with realistic physical components.

1-8 TIME-INVARIANT VERSUS TIME-VARYING SYSTEMS

When the parameters of a control system are stationary with respect to time during the operation of the system, the system is called a time-invariant system. In practice, most physical systems contain elements that drift or vary with time. For example, the winding resistance of an electric motor will vary when the motor is first being excited and its temperature is rising. Another example of a time-varying system is a guided-missile control system in which the mass of the missile decreases as the fuel on board is being consumed during flight. Although a time-varying system without nonlinearity is still a linear system, the analysis and design of this class of systems are usually much more complex than that of the linear time-invariant systems.

1-9 CONTINUOUS-DATA CONTROL SYSTEMS

A continuous-data system is one in which the signals at various parts of the system are all functions of the continuous time variable t . The signals in continuous-data systems may be further classified as ac or dc. Unlike the general definitions of ac and dc signals used in electrical engineering, ac and dc control systems carry special significance in control systems terminology. When one refers to an **ac control system**, it usually means that the signals in the system are *modulated* by some form of modulation scheme. A **dc control system**, on the other hand, simply implies that the signals are *unmodulated*, but they are still ac signals according to the conventional definition. The schematic diagram of a closed-loop

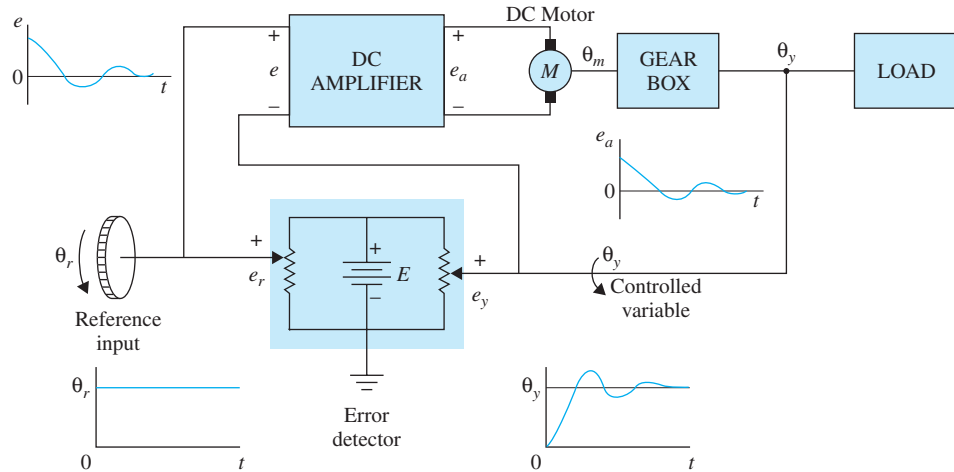


Figure 1-12 Schematic diagram of a typical dc closed-loop system.

dc control system is shown in Fig. 1-12. Typical waveforms of the signals in response to a step-function input are shown in the figure. Typical components of a dc control system are potentiometers, dc amplifiers, dc motors, dc tachometers, and so on.

Figure 1-13 shows the schematic diagram of a typical ac control system that performs essentially the same task as the dc system in Fig. 1-12. In this case, the signals in the system are modulated; that is, the information is transmitted by an ac carrier signal. Notice that the output controlled variable still behaves similarly to that of the dc system. In this case, the modulated signals are demodulated by the low-pass characteristics of the ac motor. Ac control systems are used extensively in aircraft and missile control systems in which noise and disturbance often create problems. By using modulated ac control systems with carrier frequencies of 400 Hz or higher, the system will be less susceptible to low-frequency

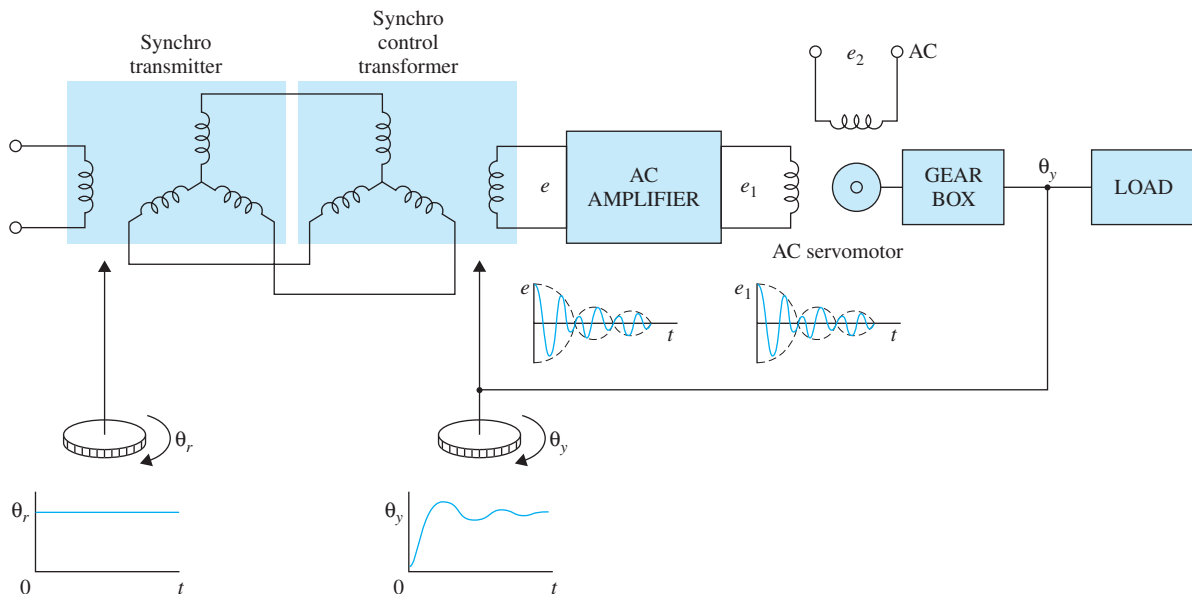


Figure 1-13 Schematic diagram of a typical ac closed-loop control system.

noise. Typical components of an ac control system are synchros, ac amplifiers, ac motors, gyroscopes, accelerometers, and so on.

In practice, not all control systems are strictly of the ac or dc type. A system may incorporate a mixture of ac and dc components, using modulators and demodulators to match the signals at various points in the system.

1-10 DISCRETE-DATA CONTROL SYSTEMS

Discrete-data control systems differ from the continuous-data systems in that the signals at one or more points of the system are in the form of either a pulse train or a digital code. Usually, discrete-data control systems are subdivided into **sampled-data** and **digital control systems**.

Digital control systems are usually less susceptible to noise.

Sampled-data control systems refer to a more general class of discrete-data systems in which the signals are in the form of pulse data. A digital control system refers to the use of a digital computer or controller in the system so that the signals are digitally coded, such as in binary code.

In general, a sampled-data system receives data or information only intermittently at specific instants of time. For example, the error signal in a control system can be supplied only in the form of pulses, in which case the control system receives no information about the error signal during the periods between two consecutive pulses. Strictly, a sampled-data system can also be classified as an ac system because the signal of the system is pulse modulated.

Figure 1-14 illustrates how a typical sampled-data system operates. A continuous-data input signal $r(t)$ is applied to the system. The error signal $e(t)$ is sampled by a sampling device, the **sampler**, and the output of the sampler is a sequence of pulses. The sampling rate of the sampler may or may not be uniform. There are many advantages to incorporating sampling into a control system. One important advantage is that expensive equipment used in the system may be time-shared among several control channels. Another advantage is that pulse data are usually less susceptible to noise.

Because digital computers provide many advantages in size and flexibility, computer control has become increasingly popular in recent years. Many airborne systems contain digital controllers that can pack thousands of discrete elements into a space no larger than the size of this book. Figure 1-15 shows the basic elements of a digital autopilot for aircraft attitude control.

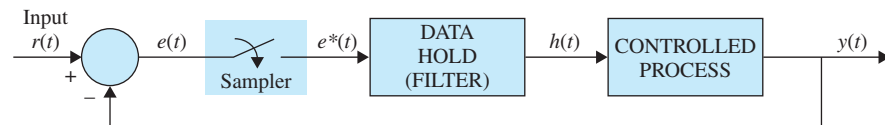


Figure 1-14 Block diagram of a sampled-data control system.

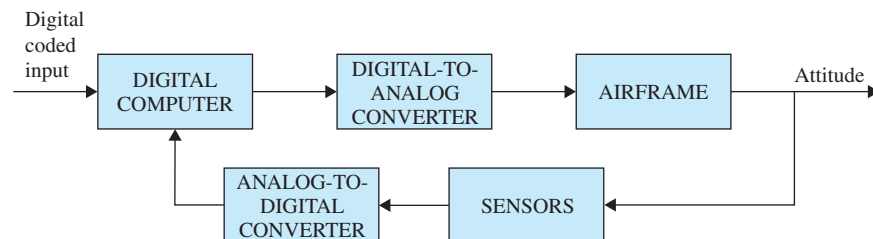


Figure 1-15 Digital autopilot system for aircraft attitude control.

1-11 CASE STUDY: INTELLIGENT VEHICLE OBSTACLE AVOIDANCE—LEGO MINDSTORMS

The goal of this section is to provide you with a better understanding of the controller design process for a practical system—in this case a **LEGO® MINDSTORMS® NXT** programmable robotic system. Note the example used here may appear too difficult at this stage but it can demonstrate the steps you need to take for successful implementation of a control system. You may revisit this example after successful completion of App. D.

Description of the Project²

The system setup, shown in Fig. 1-16, is a LEGO MINDSTORMS car that is controlled using MATLAB® and Simulink®. The LEGO car, shown in Figs. 1-17 and 1-18, is equipped with an ultrasonic sensor, a light sensor, an indicating light, an NXT motor gearbox and the NXT brick. An encoder (sensor) is used to read the angular position of the motor gearbox. The NXT brick can take input from up to four sensors and control up to three motors, via RJ12 cables—see Chap. 8 for more details. The ultrasonic sensor is placed in the front to detect the distance from the obstacle. The light sensor is facing downward to detect the color of the running surface—in this case white means go! The system interfaces with the host computer using a USB connection, while the host computer logs encoder data in real-time using a Bluetooth connection.

The Controller Design Procedure

The design of a control system for a practical problem requires a systematic treatment as follows:

- Outline the objectives of the control system.
- Specify the requirements, design criteria, and constraints (Chaps. 7 and 11).

²Instructional YouTube video: <http://youtu.be/gZo7qkWlZhs>.

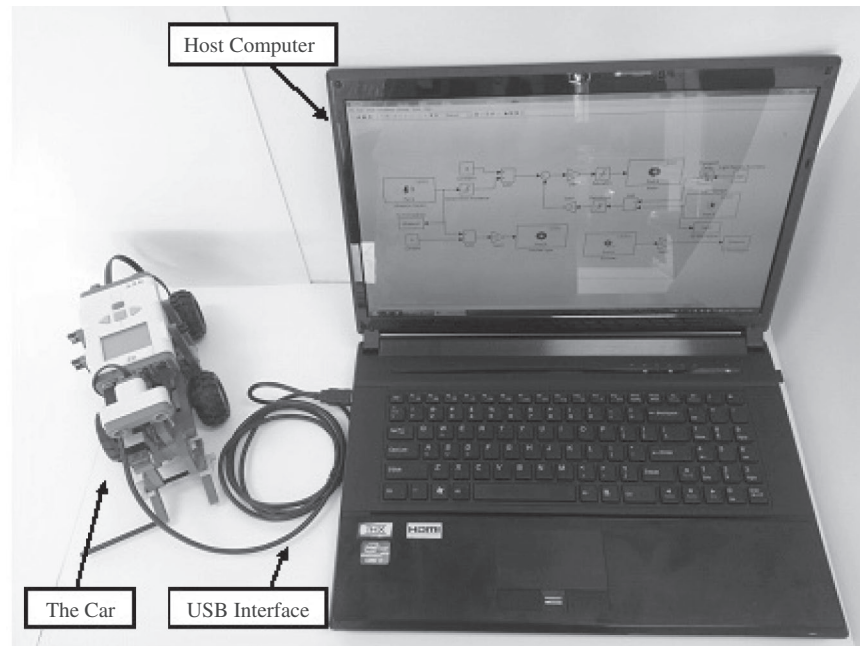


Figure 1-16 Final car product with host computer.

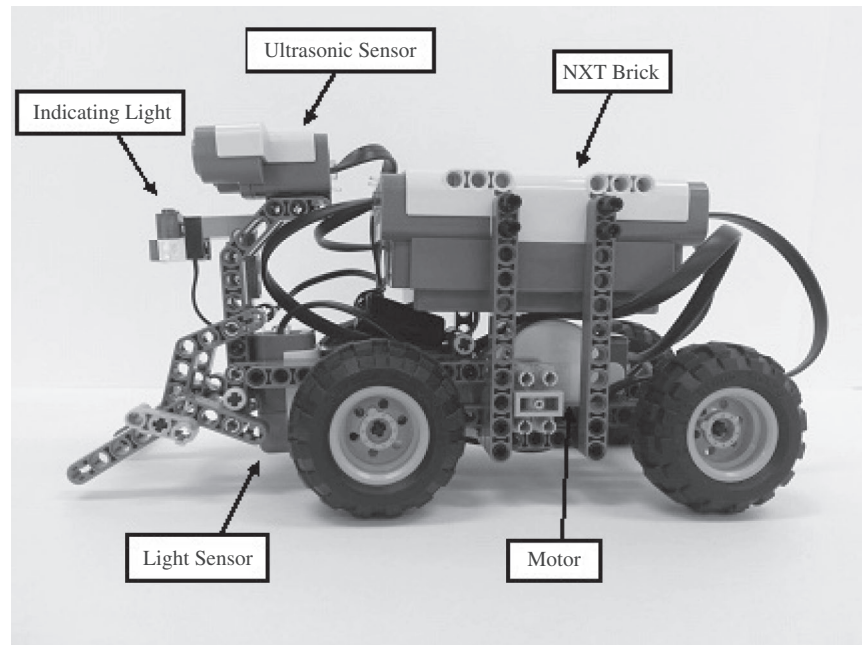


Figure 1-17 Car design—side view.

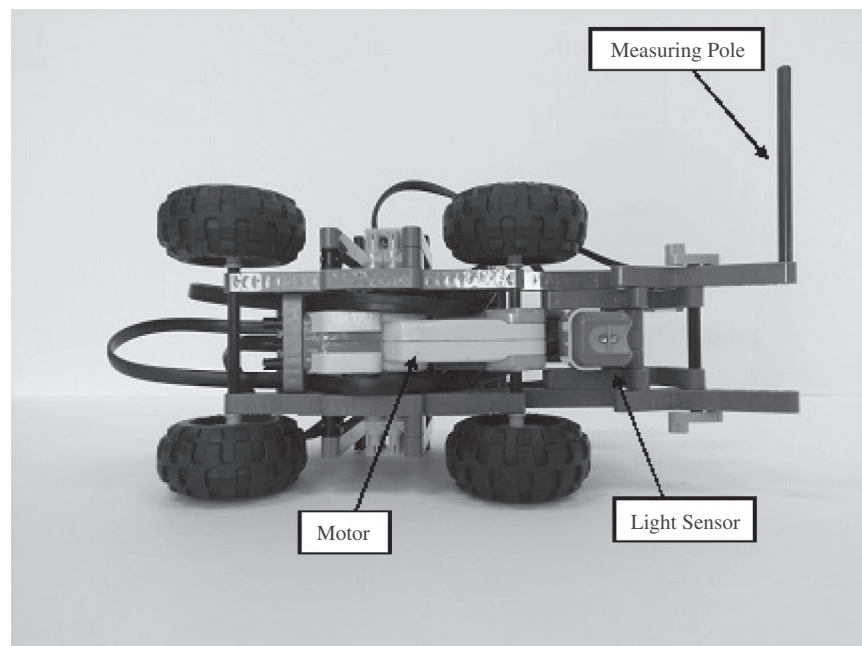


Figure 1-18 Car design—bottom view.

- Develop a mathematical model of the system, including mechanical, electrical, sensors, motor, and the gearbox (Chaps. 2, 3, and 6).
- Establish how the overall system subcomponents interact, utilizing block diagrams (Chap. 4).
- Use block diagrams, signal flow graphs, or state diagrams to find the model of the overall system—transfer function or state space model (Chap. 4).
- Study the transfer function of the system in the Laplace domain, or the state space representation of the system (Chap. 3).
- Understand the time and frequency response characteristics of the system and whether it is stable or not (Chaps. 5, 7, and 9 to 11).
- Design a controller using time response (Chaps. 7 and 11).
- Design a controller using the root locus technique (in the Laplace domain) and time response (Chaps. 7, 9, and 11).
- Design a controller using frequency response techniques (Chaps. 10 and 11).
- Design a controller using the state space approach (Chap. 8).
- Optimize the controller if necessary (Chap. 11).
- Implement the design on the experimental/practical system (Chaps. 7 and 11 and App. D).

Objective

The objective of this project is to have the LEGO car running on a white surface and stop just before hitting an obstacle—in this case a wall.

Design Criteria and Constraints

The car can only be running at full speed on a white surface. The car must stop, if the surface color is not white. The car must also stop just before hitting an obstacle.

Develop a Mathematical Model of the System

The motor drives the rear wheels. The vehicle mass, motor, gearbox, and wheel friction must be considered in the modeling process. You may use Chaps. 2 and 6 to arrive at the mathematical model of the system. Also check Sec. 7-5.

Following the process in Chaps. 6 and 7 and App. D, **the block diagram** of the system using position control (using an amplifier with gain K) and the encoder sensor position feedback is shown in Fig. 1-19, where system parameters and variables, in time domain, include

R_a = armature resistance, Ω

L_a = armature inductance, H

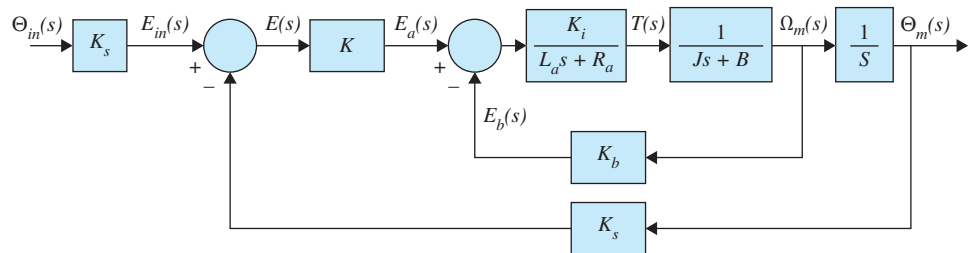


Figure 1-19 Block diagram of a position-control, armature-controlled dc motor representing the LEGO car.

θ_m = angular displacement of the motor gearbox shaft, radian

θ_{in} = desired angular displacement of the motor gearbox shaft, radian

ω_m = angular speed of the motor shaft, rad/s

T = torque developed by the motor, N · m

J = equivalent moment of inertia of the motor and load connected to the motor shaft,

$J = J_L/n^2 + J_m$, kg · m² (refer to Chap. 2 for more details)

n = gear ratio

B = equivalent viscous-friction coefficient of the motor and load referred to the motor shaft, N · m/rad/s (in the presence of gear ratio, B must be scaled by n ; refer to Chap. 2 for more details)

K_i = torque constant, N · m/A

K_b = back-emf constant, V/rad/s

K_s = equivalent encoder sensor gain, V/rad

K = position control gain (amplifier)

The closed-loop **transfer function**, in Laplace domain, in this case becomes

$$\frac{\Theta_m(s)}{\Theta_{in}(s)} = \frac{\frac{KK_iK_s}{R_a}}{(\tau_e s + 1) \left\{ Js^2 + \left(B_m + \frac{K_b K_i}{R_a} \right) s + \frac{KK_iK_s}{R_a} \right\}} \quad (1-7)$$

where K_s is the sensor gain. The motor electrical time constant $\tau_e = L_a/R_a$ may be neglected for small L_a . As a result the position transfer function is simplified to

$$\frac{\Theta_m(s)}{\Theta_{in}(s)} = \frac{\frac{KK_iK_s}{R_a J}}{s^2 + \left(\frac{R_a B_m + K_i K_b}{R_a J} \right) s + \frac{KK_iK_s}{R_a J}} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (1-8)$$

where Eq. (1-8) is a second-order system, and

$$2\zeta\omega_n = \frac{R_a B_m + K_i K_b}{R_a J} \quad (1-9)$$

$$\omega_n^2 = \frac{KK_iK_s}{R_a J} \quad (1-10)$$

The transfer function in Eq. (1-8) represents a **stable** system for all $K > 0$ and will not exhibit **any steady state error**—that is, it will reach the desired destination dictated by the input.

In order to study the time response behavior of the position-control system, we use Simulink. The Simulink numerical model of the system is shown in Fig. 1-20, where all system parameters may be obtained experimentally using the procedure discussed in Chap. 8, as shown in Table 1-1.

After running the simulation for the controller gain $K = 12.5$, we can plot the car travel as shown in Fig. 1-21. Note encoder output was scaled to arrive at the results shown.

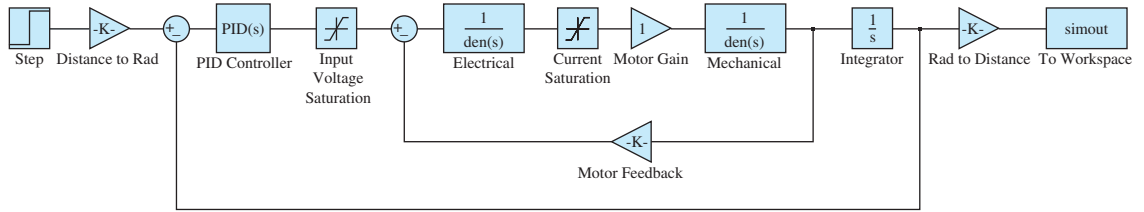


Figure 1-20 Car Simulink model.

TABLE 1-1 LEGO Car System Parameters

Car mass	$M = 574 \text{ g}$
Armature resistance	$R_a = 2.27 \Omega$
Armature inductance	$L_a = 0.0047 \text{ H}$
Motor torque constant	$K_t = 0.25 \text{ N} \cdot \text{m/A}$
Back-EMF constant	$K_b = 0.25 \text{ V/rad/s}$
Equivalent viscous-friction coefficient	$B = 0.003026 \text{ kg} \cdot \text{m}^2/\text{s or } \text{N} \cdot \text{m/s}$
Total moment of inertia	$J = 0.00246 \text{ kg} \cdot \text{m}^2$

As shown, the car travels at a constant speed from 1 to approximately 2.7 s before stopping. From the slope of the graph in Fig. 1-21, we can obtain the maximum speed of the car as 0.4906 m/s. This is also confirmed using the speed plot in Fig. 1-22. Furthermore, from this graph, we can find the average acceleration of the car as 2.27 m/s². The stoppage time is dictated by the system mechanical time constant where the speed, as shown in Fig. 1-22, decays exponentially from maximum to zero. This time must be taken into consideration when the actual system meets an obstacle.

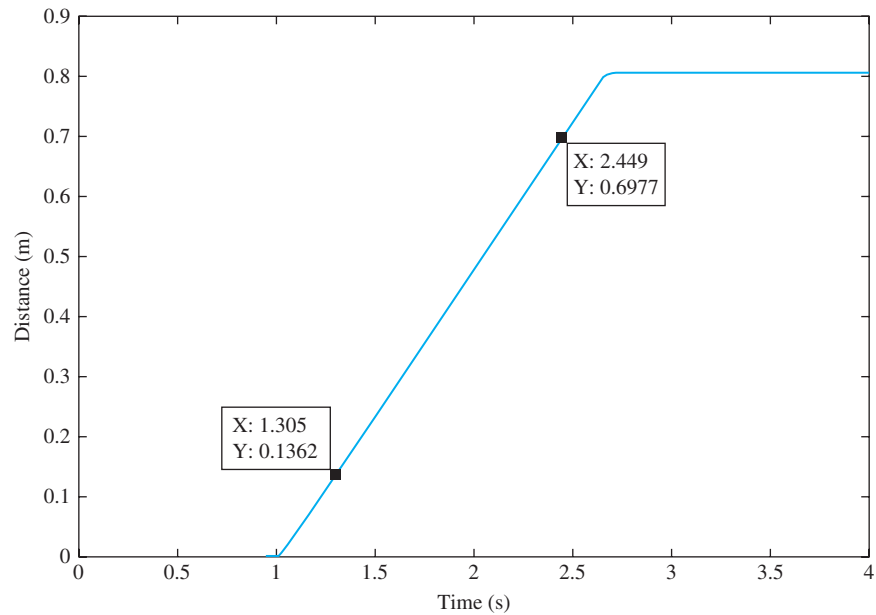


Figure 1-21 Car travel.

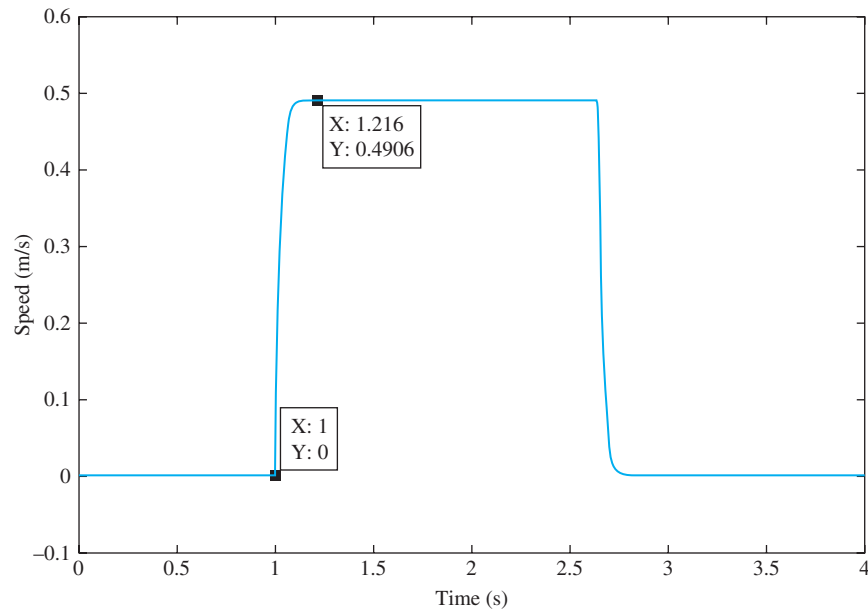


Figure 1-22 Car speed graph.

Once a satisfactory response is obtained, the control system can be tested on the **actual system**. The LEGO car utilizes Simulink to operate. The Simulink model in this case is built based on the process indicated in Chap. 8 and is shown in Fig. 1-23. Remember to enter the gain parameter $K = 12.5$.

After the Simulink model is built, you can pair the host computer with the NXT brick using Bluetooth—see the instructional video. We must first start by connecting the car to the host computer using the USB cable and selecting Run on Target Hardware in the Simulink Tools menu. When the indicating light illuminates, the car is operational. For the car to run wirelessly, simply unplug the USB cable at this point.

To start up the car, you can place a strip, which is not white, underneath the light sensor, as shown in Fig. 1-24. By pulling the strip out, the car will start its run. When the car reaches an obstacle, the indicating light will turn off as it comes to a halt, as shown in Fig. 1-25—see the instructional video to learn more about the ultrasonic sensor shown in the Simulink

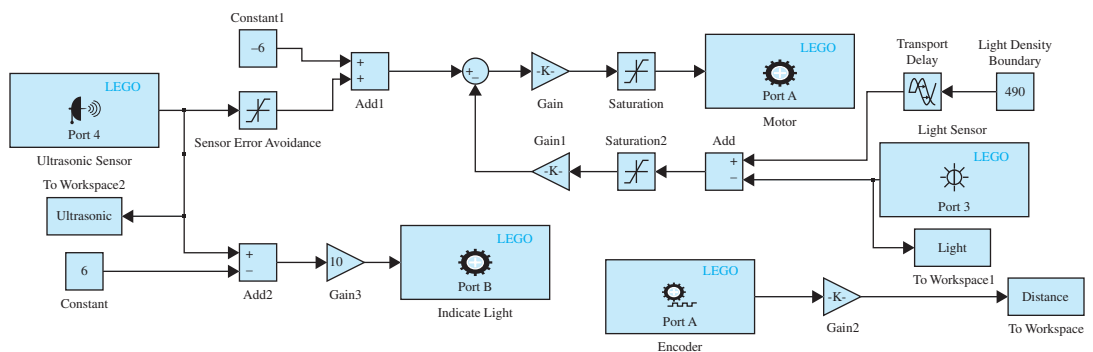


Figure 1-23 Simulink model to operate the LEGO car.

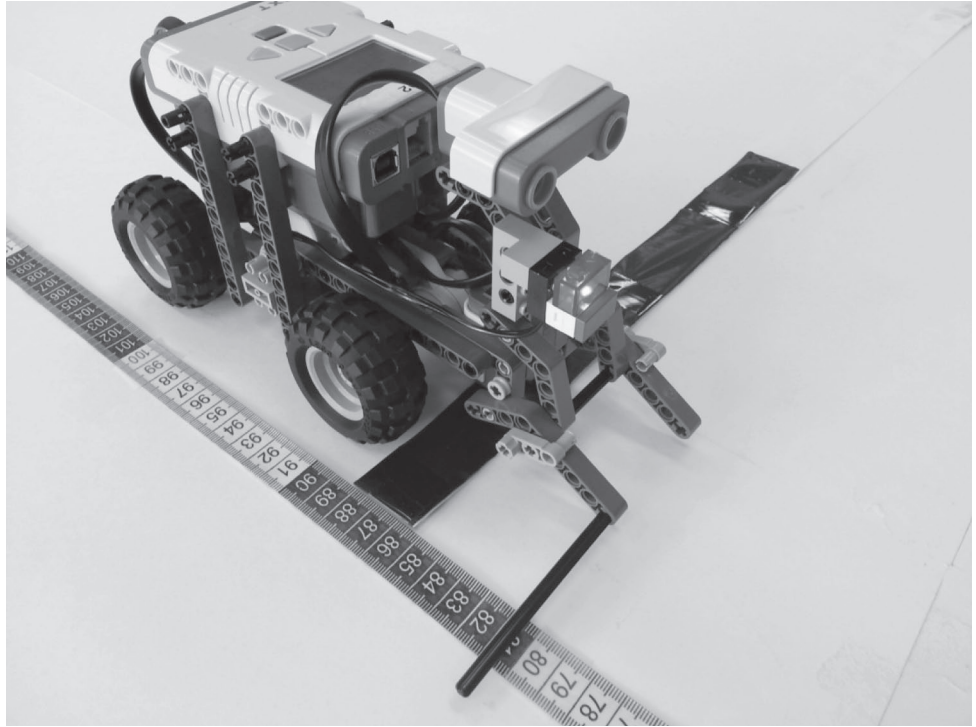


Figure 1-24 Starting position.

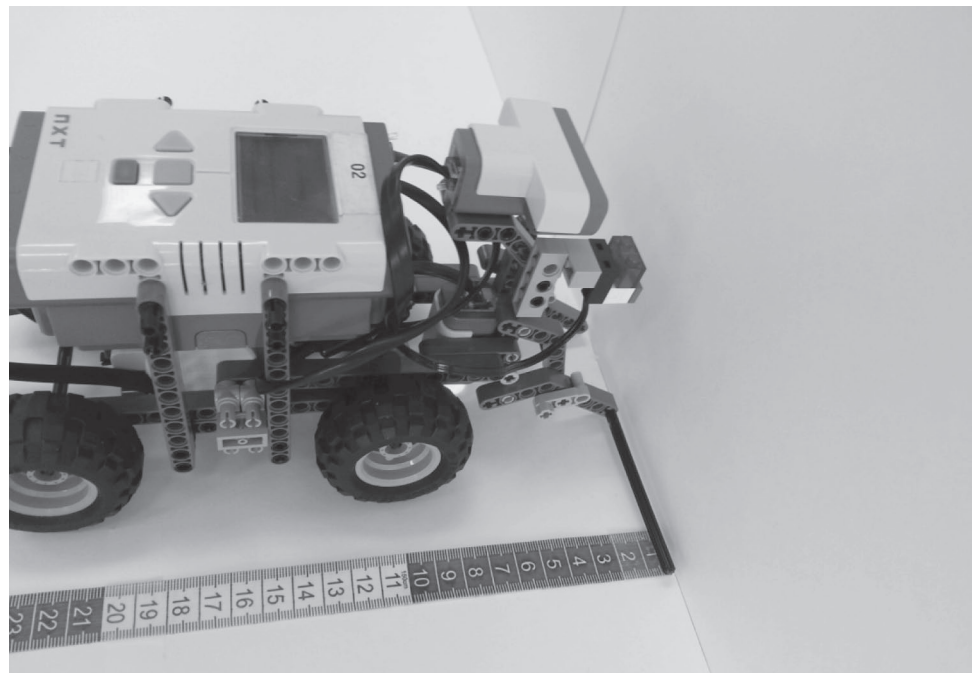


Figure 1-25 Final position.

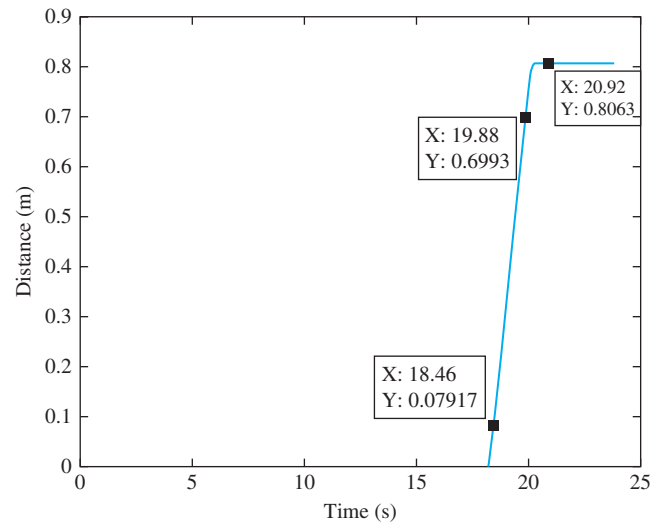


Figure 1-26 Car travel from motor encoder.

model in Fig. 1-23. After the car has finished its run, click Stop in the Simulink program to stop the operation. All data will be stored in the computer. Using MATLAB you can plot the vehicle time response—as illustrated in Chap. 8. As shown in Fig. 1-26, the speed of the car is 0.4367 m/s, which is close to the numerical simulation results. The distance that car traveled to reach the wall is 0.8063 m. From the speed plot, shown in Fig. 1-27, the average acceleration is 1.888 m/s^2 .

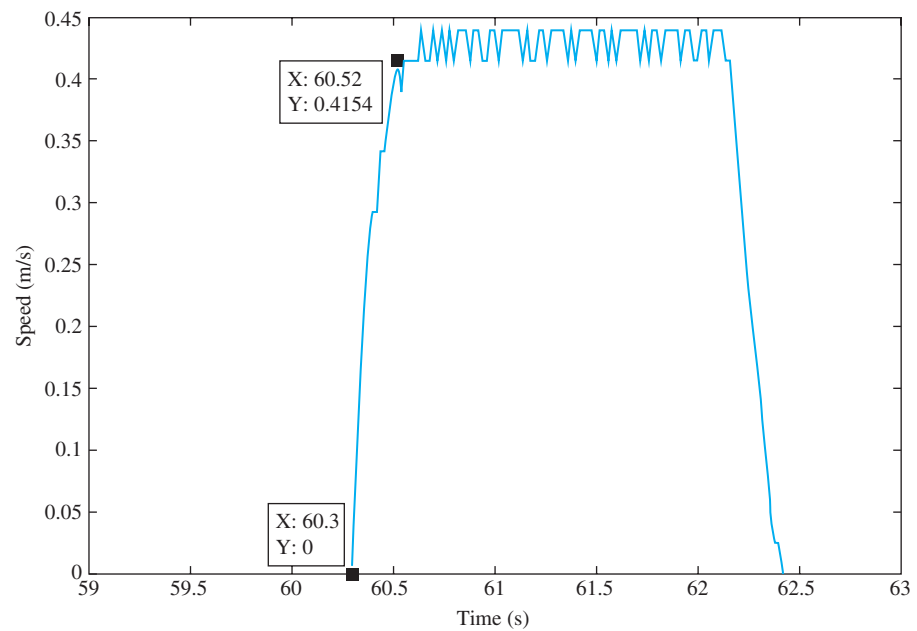


Figure 1-27 Car speed plot.

1-12 SUMMARY

In this chapter, we introduced some of the basic concepts of what a control system is and what it is supposed to accomplish. The basic components of a control system were described. By demonstrating the effects of feedback in a rudimentary way, the question of why most control systems are closed-loop systems was also clarified. Most important, it was pointed out that feedback is a double-edged sword—it can benefit as well as harm the system to be controlled. This is part of the challenging task of designing a control system, which involves consideration of such performance criteria as stability, sensitivity, bandwidth, and accuracy. Finally, various types of control systems were categorized according to the system signals, linearity, and control objectives. Several typical control-system examples were given to illustrate the analysis and design of control systems. Most systems encountered in real life are nonlinear and time varying to some extent. The concentration on the studies of linear systems is due primarily to the availability of unified and simple-to-understand analytical methods in the analysis and design of linear systems.