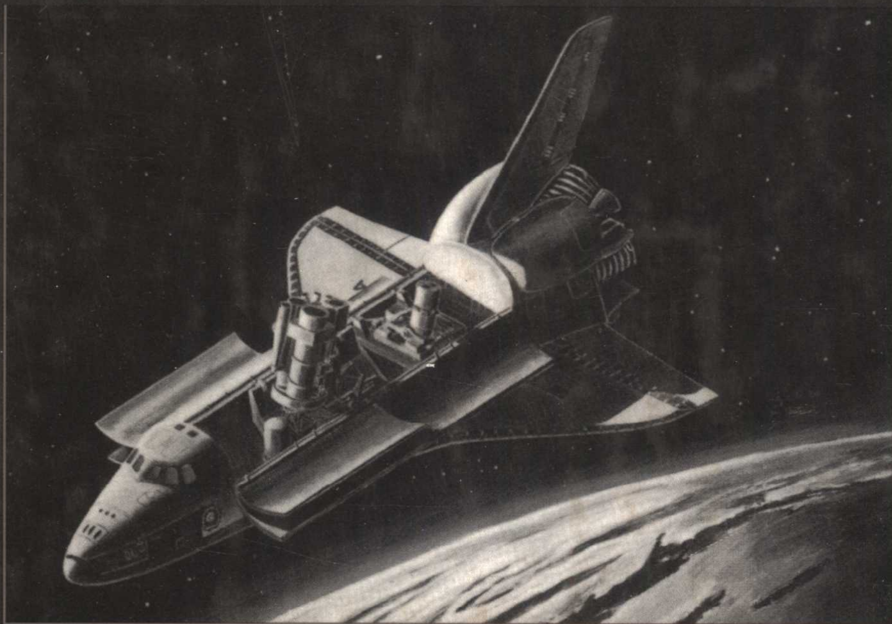
FRANCIS H. RAVEN



Automatic Control Engineering

Fifth Edition

AUTOMATIC CONTROL ENGINEERING

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Francis H. Raven

Professor of Mechanical Engineering
University of Notre Dame

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ABOUT THE AUTHOR

Francis H. Raven is Professor of Aerospace and Mechanical Engineering at the University of Notre Dame. He is the author of *Mathematics of Engineering Systems* and *Engineering Mechanics,* both published by McGraw-Hill, Inc. Dr. Raven originated the method of independent position equations, a generalized analytical method for kinematic analysis. Presently he is involved in research in the Robotics and Programmed Automation Laboratory at the University of Notre Dame.

Professor Raven received his Ph.D. in Mechanical Engineering from Cornell University. As a control engineer at the Hamilton Standard Division, United Technologies, he obtained extensive experience in the design of hydraulic and pneumatic control systems. He now does consulting for a variety of industries, some of which includes the design of computer controlled systems.

Dr. Raven is listed in the international *Who's Who in Engineering*, *Engineers of Distinction, and Who's Who in the Midwest.* He is the recipient of the AT&T award for excellence in teaching, presented by the American Society for Engineering Education.

PREFACE

In recent years, automatic control systems have been rapidly increasing in importance in all fields of engineering. The applications of control systems cover a very wide range, from the design of precision control devices such as delicate electronic equipment to the design of massive equipment such as that used for the manufacture of steel or other industrial processes. Microprocessors have added a new dimension to the capability of control systems. New applications for automatic controls are continually being discovered.

This text is the outgrowth of notes developed by the author to teach control engineering at the University of Notre Dame. The author has endeavored to give the principles a thorough presentation and yet make them clear and easy to understand. It is assumed that the reader has the general maturity and background of a third- or fourth-year engineering student, but no previous training in control engineering.

Although the principles of feedback control systems are presented in a manner which is appropriate to the interests of mechanical engineers, this text has also been successfully used to teach students in other fields of engineering. In addition, the author has taught night courses for practicing engineers. In the light of their enthusiastic comments, it is felt that this book will be of much value to the engineer in industry who did not have the opportunity to take such a course while in college.

The study of control systems is begun by showing how to obtain the equation of operation for each component in a system. It is then shown how each of these equations may be represented as a block diagram. Each of these block diagrams is connected to form the overall block-diagram representation for the entire system, just as the actual components are connected to form the complete control system. This overall block diagram is a very helpful representation of the differential equation that describes the operation of the system. Because actual control systems frequently contain nonlinear components, considerable emphasis is given to such components. This material is presented in the first three chapters. In Chap. 4, it is shown that much important information concerning the basic or inherent operating characteristics of a system may be obtained from knowledge of the steady-state behavior.

This introduction to control theory differs from the usual blackbox approach, in which the block diagram for a system is given outright. The blackbox approach permits the introduction of Laplace transforms and other methods of system analysis at an earlier stage. However, it has been the author's experience that students achieve deeper understanding of the various techniques used in system analysis if students are first familiarized with the physical significance of feedback controls by knowing how to obtain the differential equation that describes the operation of a system.

In Chap. 5, it is shown how the linear differential equations which describe the operation of control systems may be solved algebraically by the use of Laplace transforms. It is seen that this method reveals directly much interesting information about systems. General characteristics of transient behavior are described in Chap. 6. It is pointed out that the transient response is governed by the location of the roots of the characteristic equation. It is also shown how to program a digital computer for investigating the performance of control systems. The application of the root-locus method to the design of control systems is the topic of Chap. 7. The use of the analog computer to simulate control systems is explained in Chap. 8.

State-space methods are presented in Chap. 9. It is shown how the concepts of classical control theory are combined with state-space concepts to yield the "modern" control theory. By seeing how modern control theory builds on classical methods, the reader attains both a better understanding of modern methods and a deeper appreciation of the classical formulation. Digital computers and microprocessors are becoming increasingly important as elements of control systems. As explained in Chap. 10, most of the methods (both classical and modern) used in the design of continuous-data systems may be extended to digital control systems. The term "digital control system" comprises a broad class of systems including computer-controlled systems, discrete data systems, sampled-data systems, and timesharing systems. The use of frequency-response techniques to evaluate dynamic performance is explained in Chaps. 11 and 12.

The author wishes to express his appreciation for the many fine suggestions made by teachers who have used the previous editions. These suggestions have been of great value in the preparation of the fifth edition. Special gratitude is owed to Anuradha Annaswany, Michigan Institute of Technology; Allen Arthur, University of Cincinnati; Frank D'Souza, Illinois Institute of Technology; David Hullender, University of Texas at Arlington; Suhada Jayasuriya, Texas A&M University; Scott Kimbrough, University of Utah; Richard Klafter, Temple University; Lee J. LaFrance, New Mexico State University; Ching Li, Columbia University; Ronald A. Perez, University of Wisconsin, Milwaukee; Nader Sadegh, Georgia Tech; F. H. Speckhart, University of Tennessee; Gerald Whitehouse, Louisiana State University; and William Wainwright, University of Colorado, who reviewed the entire manuscript for this edition. Students have also been very helpful in their comments. Particular recognition is due to Linda F. Raven.

The author also wishes to express his gratitude for the continued encouragement of his colleagues at the University of Notre Dame, especially to Dr. Thomas J. Mueller, chairman of the Department of Aerospace and Mechanical Engineering.

Thanks are also due to Kelly Marie Keller, Martha Van Overberghe, and Lisa Tranberg for typing the numerous revisions of the notes from which this textbook has been developed.

The author's wife, Therese, has faithfully worked with him throughout the development of this text. She has made innumerable suggestions and has been a constant source of encouragement.

Francis H. Raven

CONTENTS

CHAPTER 1

INTRODUCTION TO AUTOMATIC CONTROLS

1.1 HISTORICAL DEVELOPMENT

Early people had to rely upon their own brute strength or that of animals to supply energy for doing work. By the use of simple mechanical devices such as wheels and levers, people accomplished such feats as the building of high pyramids and Roman highways and aqueducts. They first supplemented their energy and that of beasts by utilizing power from natural sources, such as the wind for powering sailing vessels and windmills and waterfalls for turning waterwheels. The invention of the steam engine was a milestone in human progress because it provided people with useful power that could be harnessed at will. Since then, people have devised many different means of obtaining abundant and convenient sources of energy. Engineering effort is primarily concerned with the practical applications of using power to serve human purposes. That is, the engineer designs and develops machines and equipment by which people can utilize power.

A manually controlled system is shown in Fig. 1.1*a*. It is desired to maintain the fluid in the tank at a fixed height H so that the pressure at the outlet will remain constant. The quantity of flow out from the tank Q_{out} varies with the demand. The

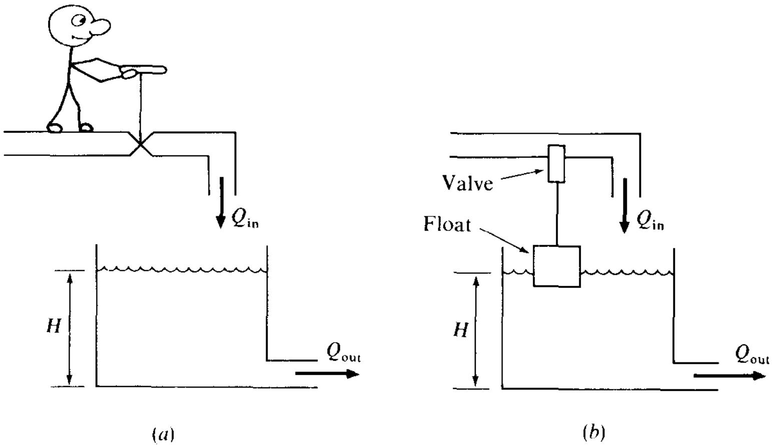

FIGURE 1.1
Pressure control systems (*a*) manual and (*b*) automatic.

operator opens or closes a valve to regulate the rate of flow into the tank Q_{in} and thus maintain the desired height of fluid in the tank.

The same system automatically controlled is shown in Fig. 1.1*b*. The height of fluid in the tank is measured by the float. When the level rises, so does the float, which in turn raises the valve to decrease the amount of flow going into the tank. Similarly, when the level drops, then the float and the valve are lowered, which increases the amount of flow going into the tank. Thus, the rate of flow into the tank is automatically regulated so as to maintain the desired height of fluid in the tank. By placing a turnbuckle on the rod connecting the float and the valve, the length of the rod can be changed. Thus, the desired height of fluid in the tank can be adjusted.

Early machines and equipment had controls which were predominantly of a manual nature, and the adjustments had to be reset frequently to maintain the desired output or performance. The design of newer equipment with greater usefulness and capabilities is bringing about an ever-increasing growth in the development of control equipment. There are two reasons. First, automatic controls relieve people of many monotonous activities so that they can devote their abilities to other endeavors. Second, modern complex controls can perform functions which are beyond the physical abilities of people to duplicate. For example, an elaborate automatic control system operates the engine of a modern jet airplane with only a minimum amount of the pilot's attention so that the pilot is free to maneuver and fly the airplane.

It is interesting to note that as the applications and uses for controls have increased, so also have the demands upon the performance of these systems increased. There is no doubt that a major concern of the engineer today, and even more so in the future, is the design and development of automatic control systems.

1.2 FEEDBACK CONTROL SYSTEMS

Various forms of transportation are illustrated in Fig. 1.2. All the basic concepts of feedback control systems are contained in each of these means of transportation. For the basic form of transportation, walking, the desired speed at which the walker wishes to go is the reference input. When the walker takes a leisurely stroll through a park, the desired speed is slow. When the person is in a hurry, the desired speed is fast. The actual speed is the controlled variable (i.e., the quantity being controlled). The part of a system which compares the reference input (desired value) with the controlled variable (actual value) in order to measure the error is called the *comparator*. The brain serves as the comparator for the walker. Typically, the error signal goes to a power-amplifying device (muscles in the legs) which actuates the system to be controlled so as to reduce the error to zero. Thus, the actual speed is the same as the desired speed.

The driver of a car compares the actual speed with the desired speed. Again the brain serves as the comparator. In response to the error signal, the driver changes the position of the accelerator pedal. The engine serves as the power-amplifying device. That is, a little motion of the accelerator pedal causes a substantial change in the power produced by the engine.

For cruise control, a magnet is attached to the driveshaft which rotates at some constant times the speed of the wheels. A magnetic pickup fixed to the body of the car generates a pulse every time the driveshaft makes one complete rotation. The rate at which pulses are being generated is a measure of the actual speed of the car. At the instant the cruise control is set, the rate at which pulses are being generated is stored so as to serve as the reference input (i.e., desired speed). A vacuum-operated device is attached to the accelerator linkage. When the actual speed is greater than the reference speed, the rate at which pulses are being generated is greater than the reference value. This error signal goes to the vacuum device which serves as a power amplifier to change the position of the accelerator linkage so as to decrease the actual speed.

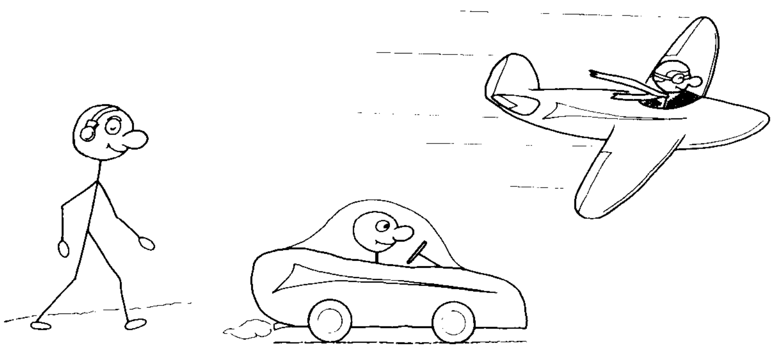

FIGURE 1.2
Various forms of transportation.

The most difficult problem which the Wright brothers encountered in the process of making the airplane into a useful machine was the control problem. After much experimentation, they developed an ingenious pulley system to coordinate the motion of the aileron and the rudder so as to produce a smooth turning effort. Note that the pilot (Orville or Wilbur) would compare the actual path of the plane with the desired path, and then in response to the error signal he would actuate the pulley system. Aerodynamic forces acting on the wings and rudder would serve as the power-amplifying device to change the trajectory of the plane. Although modern airplanes have much more sophisticated means for controlling the position of the ailerons and rudder, the principles are still the same.

The controlling of temperature is a typical example of a feedback control system. The position of the temperature dial sets the desired temperature (i.e., the reference input). The actual temperature of the system is the controlled variable (i.e., the quantity which is being controlled). The thermostat, or comparator, compares the actual temperature with the desired temperature in order to measure the error. This error signal is the actuating signal, which is then sent to the heating units in order to correct the temperature. For example, if the actual temperature is less than the desired temperature, the actuating signal causes the heating elements to supply more heat. If there is no error, the actuating signal does not change the amount of heat which is being supplied. When the actual temperature is greater than the desired value, then the actuating signal calls for a decrease in the amount of heat.

For a system to be classified as a feedback control system, it is necessary that the controlled variable be fed back and compared with the reference input. In addition, the resulting error signal must actuate the control elements (power-amplifying device) to change the output so as to minimize the error. A feedback control system is also called a *closed-loop system*. Any system which incorporates a thermostat to control temperature is a feedback, or closed-loop, system. Well-known examples are electric frying pans, irons, refrigerators, and household furnaces with thermostatic control.

For speed control systems, the device which subtracts the feedback signal from the reference input (i.e., the comparator) is often a centrifugal governor. The compression of a spring sets a force which is a measure of the desired speed. The centrifugal force of the flyweights is a measure of the actual speed. The difference in these forces is a measure of the error. The governor serves the same purpose that the thermostat does for temperature controls. That is, the governor compares the actual speed with the desired value and measures the error. This error signal then goes to a power amplifier such as a hydraulic servomotor that controls the position of a flow valve which in turn determines the rate of fuel flow to the engine. The same basic concepts apply to all types of feedback control systems, whether the controlled variable is temperature, speed, pressure, flow, position, force, torque, or any other physical quantity.

In an open-loop system, there is no comparison of the controlled variable with the desired input. Each setting of the input determines a fixed operating position for the control elements. For example, for a given input temperature setting, the heating units are positioned to supply heat at a fixed rate. Note that there is no comparator, or thermostat, which measures the error and resets the heating units. The disadvantage of such a system is illustrated by the fact that if a fixed rate of heat is supplied to a house, the inside temperature will vary appreciably with changes in the outside temperature. Thus, for a given set input to an open-loop system, there may be a big variation of the controlled variable depending on the ambient temperature.

In this example, the ambient temperature is an external disturbance. By an external disturbance is meant something external to the system which acts to change or disturb the controlled variable. A major advantage of employing feedback control is that, because of the comparator, the actuating signal continually changes so that the controlled variable tends to become equal to the reference input regardless of the external disturbance. Another consideration is that with feedback one can generally use relatively inexpensive components and yet obtain better control than is possible with very expensive components in an open-loop system. The primary focus of this text is feedback control systems.

1.3 SYSTEM REPRESENTATION

The mathematical relationships of control systems are usually represented by block diagrams. These diagrams have the advantage of indicating more realistically the actual processes which are taking place, as opposed to a purely abstract mathematical representation. In addition, it is easy to form the overall block diagram for an entire system by merely combining the block diagrams for each component or part of the system.

A comparator subtracts the feedback signal from the reference input r. For the case in which the controlled variable c is fed back directly (i.e., for unity-feedback systems), the signal coming from the comparator is $r - c$, which is equal to the actuating signal e. The mathematical relationship for this operation is

$$e = r - c \tag{1.1}$$

As illustrated in Fig. 1.3, the circle is the symbol used to indicate a summing operation. The arrowheads pointing toward the circle indicate input quantities, while the arrowhead leading away signifies the output. The sign at each input arrowhead indicates whether the quantity is to be added or subtracted.

The portion of a system between the actuating signal e and the controlled variable c is called the *control elements*. The relationship between the actuating signal e, which enters the control elements, and the controlled variable c, which is the output of the control, is expressed by the equation

$$c = G(D)e \tag{1.2}$$

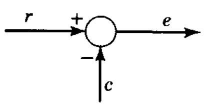

FIGURE 1.3
Block diagram of a comparator.

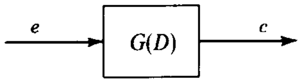

FIGURE 1.4
Block diagram of the control elements.

where $G(D)$ represents the operation of the control elements. In Chaps. 2 and 3, it is shown how the actual values of $G(D)$ for specific control systems are obtained. The block-diagram representation for the preceding equation is shown in Fig. 1.4. A box is the symbol for multiplication. In this case, the input quantity e is multiplied by the function in the box $G(D)$ to obtain the output c. With circles indicating summing points and with boxes, or blocks, indicating multiplication, any linear mathematical expression may be represented by block-diagram notation.

The complete block diagram for an elementary unity-feedback control system is obtained by combining Figs. 1.3 and 1.4 to yield Fig. 1.5. This diagram shows the controlled variable c being fed back to the summing point, where it is compared with the reference input r. This diagram pictorially shows why a feedback control system is also called a closed-loop system.

When the controlled variable is fed back to the comparator, it is usually necessary to convert the form of the controlled variable to a form that is suitable for the comparator. For example, in a temperature control system, the controlled temperature is generally converted to a proportional force or position for use in the comparator. This conversion is accomplished by feedback elements $H(D)$. The block-diagram representation for this more general case of a feedback control system is shown in Fig. 1.6. The signal which is fed back is

$$b = H(D)c \tag{1.3}$$

The elements represented by $H(D)$ are called the *feedback elements* because they are located in the feedback portion of the control. The control elements represented by $G(D)$ are the *feedforward elements* because of their location in the feedforward portion of the loop. The actuating signal e is now $r - b$. The actuating signal e is a measure or indication of the error.

The term *feedback control system* is a general term which applies to any system in which the controlled variable is measured and fed back to be compared with the reference input. The terms *servomechanism* and *regulator* are distinguished as follows. A servomechanism is a particular type of feedback control system in which the controlled variable is a mechanical position (e.g., the angular position of a shaft). A regulator is distinguished as a feedback control system in which the reference input, although adjustable, is held fixed, or constant, for long periods (e.g., most temperature controllers).

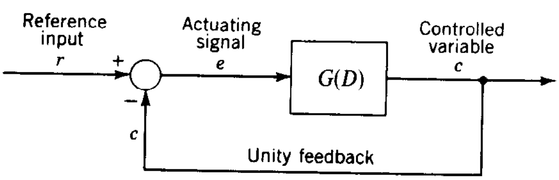

FIGURE 1.5
Block diagram of a unity-feedback control system.

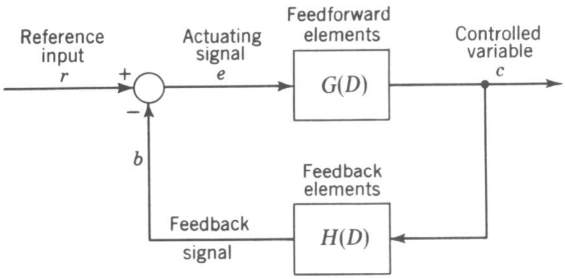

FIGURE 1.6
Block diagram of a feedback control system.

1.4 MODERN CONTROL SYSTEMS

Commercial aviation as we know it today would not be possible without modern control systems. In a blind landing (i.e., an instrument landing), the pilot gets an error signal which indicates the actual position of the plane relative to the ideal landing path. The pilot then maneuvers the plane so as to keep it on the ideal landing path. Some modern airplanes such as the Boeing 747 shown in Fig. 1.7 have a completely automated landing system (instrument landing system) which

FIGURE 1.7
The Boeing 747 airplane. (Courtesy the Boeing Company.)