CHAPTER 1

Introduction to Control Systems

OBJECTIVES

After studying this chapter, you should be able to:

- Distinguish between open-loop and closed-loop control systems.
- Understand control system block diagrams.
- Explain transfer functions.
- Differentiate between analog and digital control systems.
- Know how process control systems work.
- Know how servomechanisms work.

INTRODUCTION

A control system is a collection of components working together under the direction of some machine intelligence. In most cases, electronic circuits provide the intelligence, and electromechanical components such as sensors and motors provide the interface to the physical world. A good example is the modern automobile. Various sensors supply the on-board computer with information about the engine's condition. The computer then calculates the precise amount of fuel to be injected into the engine and adjusts the ignition timing. The mechanical parts of the system include the engine, transmission, wheels, and so on. To design, diagnose, or repair these sophisticated systems, you must understand the electronics, the mechanics, and control system principles.

In days past, so-called automatic machines or processes were controlled either by analog electronic circuits, or circuits using switches, relays, and timers. Since the advent of the inexpensive microprocessor, more and more devices and systems are being redesigned to incorporate a microprocessor controller. Examples include copying machines, soft-drink machines, robots, and industrial process controllers. Many of these machines are taking advantage of the increased processing power that comes with the microprocessor and, as a consequence, are becoming more sophisticated and are including new features. Taking again the modern automobile as an example, the original motivation for the on-board computer was to replace the mechanical and vacuum-driven subsystems used in the distributor and carburetor. Once a computer was in the design, however, making the system more sophisticated was relatively easy—for example, self-adjusting fuel/air ratio for changes in altitude. Also, features such as computer-assisted engine diagnostics could be had without much additional cost. This trend toward computerized control will no doubt continue in the future.

1.1 CONTROL SYSTEMS

Introduction and Background

In a modern **control system**, electronic intelligence controls some physical process. Control systems are the "automatic" in such things as automatic pilot and automatic washer. Because the machine itself is making the routine decisions, the human operator is freed to do other things. In many cases, machine intelligence is better than direct human control because it can react faster or slower (keep track of long-term slow changes), respond more precisely, and maintain an accurate log of the system's performance.

Control systems can be classified in several ways. A **regulator system** automatically maintains a parameter at (or near) a specified value. An example of this is a home-heating system maintaining a set temperature despite changing outside conditions. A **follow-up system** causes an output to follow a set path that has been specified in advance. An example is an industrial robot moving parts from place to place. An **event control system** controls a sequential series of events. An example is a washing machine cycling through a series of programmed steps.

Natural control systems have existed since the beginning of life. Consider how the human body regulates temperature. If the body needs to heat itself, food calories are converted to produce heat; on the other hand, evaporation causes cooling. Because evaporation is less effective (especially in humid climates), it is not surprising that our body temperature (98.6°F) was set near the high end of Earth's temperature spectrum (to reduce demand on the cooling system). If temperature sensors in the body notice a drop in temperature, they signal the body to burn more fuel. If the sensors indicate too high a temperature, they signal the body to sweat.

Man-made control systems have existed in some form since the time of the ancient Greeks. One interesting device described in the literature is a pool of water that could never be emptied. The pool had a concealed float-ball and valve arrangement similar to a toilet tank mechanism. When the water level lowered, the float dropped and opened a valve that admitted more water.

Electrical control systems are a product of the twentieth century. Electromechanical relays were developed and used for remote control of motors and devices. Relays and switches were also used as simple logic gates to implement some intelligence. Using vacuum-tube technology, significant development in control systems was made during World War II. Dynamic position control systems (servomechanisms) were developed for aircraft applications, gun turrets, and torpedoes. Today, position control systems are used in machine tools, industrial processes, robots, cars, and office machines, to name a few.

Meanwhile, other developments in electronics were having an impact on control system design. Solid-state devices started to replace the power relays in motor control circuits. Transistors and integrated circuit operational amplifiers (IC op-amps) became available for analog controllers. Digital integrated circuits replaced bulky relay logic. Finally, and perhaps most significantly, the microprocessor allowed for the creation of digital controllers that are inexpensive, reliable, able to control complex processes, and adaptable (if the job changes, the controller can be reprogrammed).

The subject of control systems is really many subjects: electronics (both analog and digital), power-control devices, sensors, motors, mechanics, and *control system theory*, which ties together all these concepts. Many students find the subject of control systems to be interesting because it deals with applications of much of the theory to which they have already been exposed. In this text, we will present material in each major subject area that makes up a control system, in more or less the same order that they appear in a control system block diagram. Some readers may choose to skip over (or lightly review) chapters that may be repetitious to them.

Finally, figures in this text use *conventional current flow,* current that travels from the positive to the negative terminal. If you are familiar with electron flow, remember that the theory and "numbers" are the same; only the indicated direction of the current is opposite from what you are used to.

Every control system has (at least) a **controller** and an **actuator** (also called a final control element). Shown in the block diagram in Figure 1.1, the controller is the intelligence of the system and is usually electronic. The input to the controller is called the **set point,** which is a signal representing the desired system output. The actuator is an electromechanical device that takes the signal from the controller and converts it into some kind of physical action. Examples of typical actuators would be an electric motor, an electrically controlled valve, or a heating element. The last block in Figure 1.1 is labeled **process** and has an output labeled **controlled variable.** The process block represents the physical process being affected by the actuator, and the controlled variable is the measurable result of that process. For example, if the actuator is an electric heating element in a furnace, then the process is "heating the furnace," and the controlled variable is the temperature in the furnace. If the actuator is an electric motor that rotates an antenna, then the process is "rotating of the antenna," and the controlled variable is the angular position of the antenna.

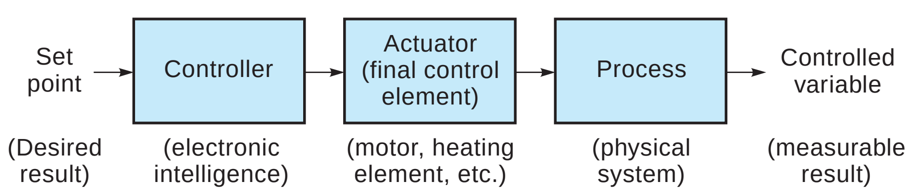


Figure 1.1
A block diagram of a control system.

Open-Loop Control Systems

Control systems can be broadly divided into two categories: open- and closed-loop systems. In an **open-loop control system,** the controller independently calculates exact voltage or current needed by the actuator to do the job and sends it. With this approach, however, *the controller never actually knows if the actuator did what it was supposed to* because there is no feedback. This system absolutely depends on the controller knowing the operating characteristics of the actuator.

EXAMPLE 1.1

Figure 1.2 shows an open-loop control system. The actuator is a motor driving a robot arm. In this case, the process is the arm moving, and the controlled variable is the angular position of the arm. Earlier tests have shown that the motor rotates the arm at 5 degrees/second (deg/s) at the rated voltage. Assume that the controller is directed to move the arm from 0° to 30°. Knowing the characteristics of the process, the controller sends a 6-second power pulse to the motor. If the motor is acting properly, it will rotate exactly 30° in the 6 seconds and stop. On particularly cold days, however, the lubricant is more viscous (thicker), causing more internal friction, and the motor rotates only 25° in the 6 seconds; the result is a 5° error. The controller has no way of knowing of the error and does nothing to correct it.

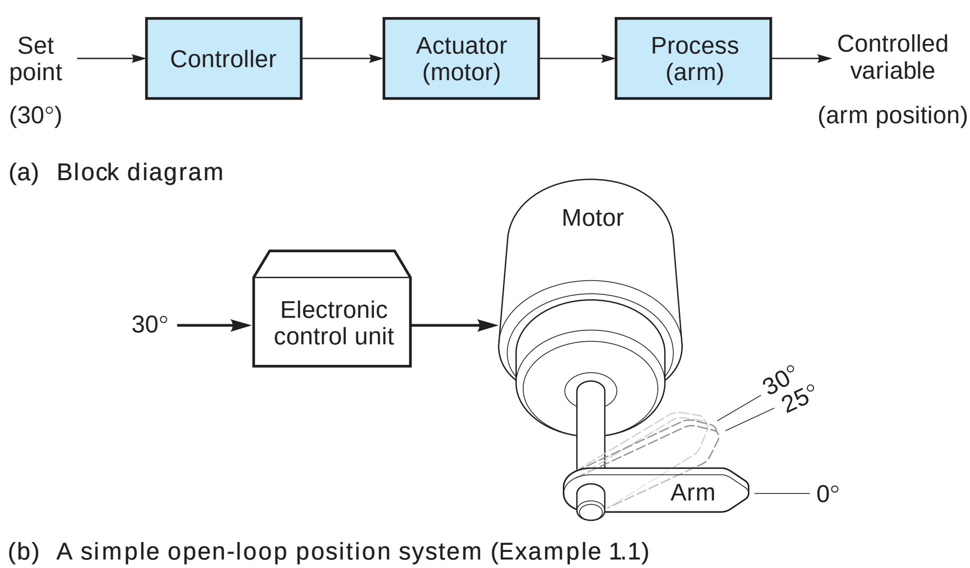


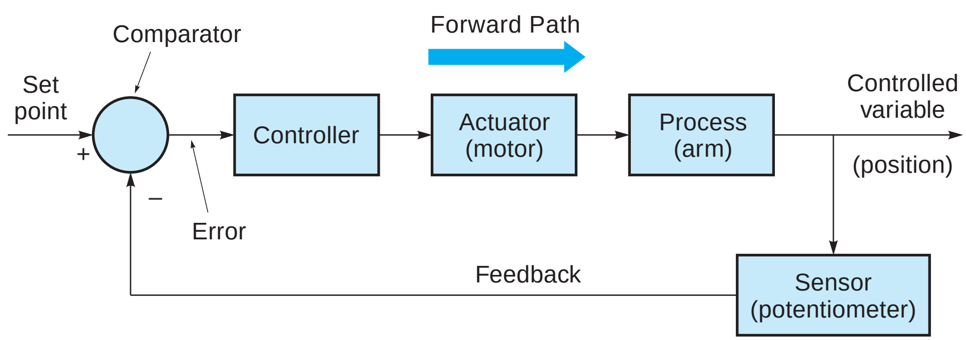
Figure 1.2
Open-loop control system.

Open-loop control systems are appropriate in applications where the actions of the actuator on the process are very repeatable and reliable. Relays and stepper motors (discussed in Chapters 4 and 8, respectively) are devices with reliable characteristics and are usually open-loop operations. Actuators such as motors or flow valves are sometimes used in open-loop operations, but they must be calibrated and adjusted at regular intervals to ensure proper system operation.

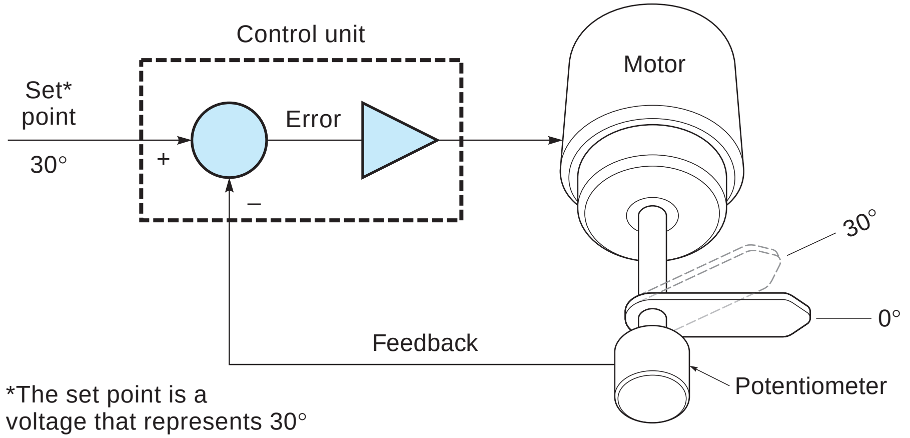
Closed-Loop Control Systems

In a **closed-loop control system,** the output of the process (controlled variable) is constantly monitored by a **sensor,** as shown in Figure 1.3(a). The sensor samples the system output and converts this measurement into an electric signal that it passes back to the controller. Because the controller knows what the system is actually doing, it can make any adjustments necessary to keep the output where it belongs. The signal from the controller to the actuator is the **forward path,** and the signal from the sensor to the

Figure 1.3
Closed-loop control system.



(a) Block diagram



(b) A simple closed-loop position system (Example 1.2) controller is the **feedback** (which "closes" the loop). In Figure 1.3(a), the feedback signal is subtracted from the set point at the **comparator** (just ahead of the controller). By subtracting the actual position (as reported by the sensor) from the desired position (as defined by the set point), we get the system **error.** The error signal represents the difference between "where you are" and "where you want to be." *The controller is always working to minimize this error signal.* A zero error means that the output is exactly what the set point says it should be.

Using a **control strategy,** which can be simple or complex, the controller minimizes the error. A simple control strategy would enable the controller to turn the actuator on or off—for example, a thermostat cycling a furnace on and off to maintain a certain temperature. A more complex control strategy would let the controller adjust the actuator force to meet the demand of the load, as described in Example 1.2.

EXAMPLE 1.2

As an example of a closed-loop control system, consider again the robot arm resting at 0° [see Figure 1.3(b)]. This time a potentiometer (pot) has been connected directly to the motor shaft. As the shaft turns, the pot resistance changes. The resistance is converted to voltage and then fed back to the controller.

To command the arm to 30°, a set-point voltage corresponding to 30° is sent to the controller. Because the actual arm is still resting at 0°, the error signal "jumps up" to 30°. Immediately, the controller starts to drive the motor in a direction to reduce the error. As the arm approaches 30°, the controller slows the motor; when the arm finally reaches 30°, the motor stops. If at some later time, an external force moves the arm off the 30° mark, the error signal would reappear, and the motor would again drive the arm to the 30° position.

The self-correcting feature of closed-loop control makes it preferable over open-loop control in many applications, despite the additional hardware required. This is because closed-loop systems provide reliable, repeatable performance even when the system components themselves (in the forward path) are not absolutely repeatable or precisely known.

Transfer Functions

Physically, a control system is a collection of components and circuits connected together to perform a useful function. *Each component in the system converts energy from one form to another;* for example, we might think of a temperature sensor as converting degrees to volts or a motor as converting volts to revolutions per minute. To describe the performance of the entire control system, we must have some common language so that we can calculate the combined effects of the different components in the system. This need is behind the transfer function concept.

A **transfer function** (TF) is a mathematical relationship between the input and output of a control system component. Specifically, the transfer function is defined as the output divided by the input, expressed as

$$TF = \frac{\text{output}}{\text{input}} \qquad 1.1$$

Technically, the transfer function must describe both the time-dependent and the steady-state characteristics of a component. For example, a motor may have an initial surge of current that levels off at a lower steady-state value. The mathematics necessary to account for the time-dependent performance is beyond the scope of this text. In this text, we will consider only *steady-state values* for the transfer function, which is sometimes called simply the **gain,** expressed as

$$TF_{\text{steady-state}} = \text{gain} = \frac{\text{steady-state output}}{\text{steady-state input}} \qquad 1.2$$

EXAMPLE 1.3

A potentiometer is used as a position sensor [see Figure 1.3(b)]. The pot is configured in such a way that 0° of rotation yields 0 V and 300° yields 10 V. Find the transfer function of the pot.

SOLUTION

The transfer function is output divided by input. In this case, the input to the pot is "position in degrees," and output is volts:

$$TF = \frac{\text{output}}{\text{input}} = \frac{10\ \text{V}}{300°} = 0.0333\ \text{V/deg}$$

The transfer function of a component is an extremely useful number. It allows you to calculate the output of a component if you know the input. The procedure is simply to multiply the transfer function by the input, as shown in Example 1.4.

EXAMPLE 1.4

For a temperature-measuring sensor, the input is temperature, and the output is voltage. The sensor transfer function is given as 0.01 V/deg. Find the sensor-output voltage if the temperature is 600°F.

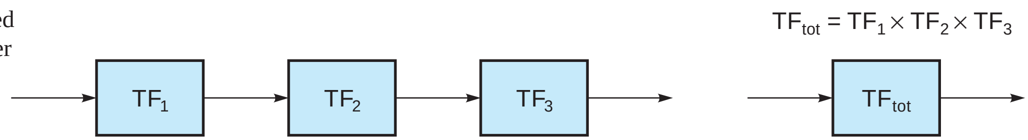
SOLUTION

If $TF = \frac{\text{output}}{\text{input}}$, then

$$\text{Output} = \text{input} \times TF$$

$$= \frac{600° \times 0.01\ \text{V}}{\text{deg}} = 6\ \text{V}$$

Figure 1.4
A series of transfer functions reduced to a single tranfer function.



(a) Individual transfer functions (b) Combined transfer function

As mentioned previously, transfer functions can be used to analyze an entire system of components. One common situation involves a series of components where the output of one component becomes the input to the next and each component has its own transfer function. Figure 1.4(a) shows the block diagram for this situation. This diagram can be reduced into a single block that has a TF_{tot}, which is the product of all the individual transfer functions. This concept is illustrated in Figure 1.4(b) and stated in Equation 1.3:*

$$TF_{tot} = \text{system gain} = TF_1 \times TF_2 \times TF_3 \times \ldots \qquad 1.3$$

where

TF_{tot} = total steady-state transfer function for the entire (open-loop) system

$TF_1, TF_2, \ldots$ = individual transfer functions

These concepts are explained in Example 1.5.

EXAMPLE 1.5

Consider the system shown in Figure 1.5. It consists of an electric motor driving a gear train, which is driving a winch. Each component has its own characteristics: The motor (under these conditions) turns at 100 rpm_m for each volt (V_m) supplied; the output shaft of the gear train rotates at one-half of the motor

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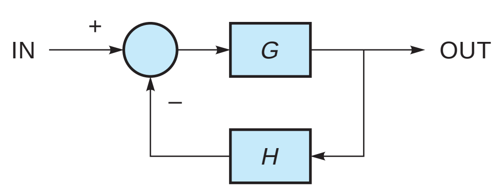
*Equation 1.3 is for open-loop systems only. If there is a feedback path (as shown in the accompanying diagram), then the overall system gain can be calculated as follows: $TF_{tot} = G/(1 + GH)$, where G is the total gain of the forward path and H is the total gain of the feedback path.



speed; the winch (with a 3-inch shaft circumference) converts the rotary motion (rpm_w) to linear speed. The individual transfer functions are given as follows:

Motor: $$TF_m = \frac{\text{output}}{\text{input}} = \frac{100\ rpm_m}{1\ V_m} = 100\ rpm_m/V$$

Gear train: $$TF_g = \frac{\text{output}}{\text{input}} = \frac{1\ rpm_w}{2\ rpm_m} = 0.5\ rpm_w$$

Winch: $$TF_w = \frac{\text{output}}{\text{input}} = \frac{3\ \text{in./min}}{1\ rpm_w} = 3\ \text{in./min}/rpm_w$$

Using Equation 1.3, we can calculate the system transfer function. If everything is correct, all units will cancel except for the desired set:

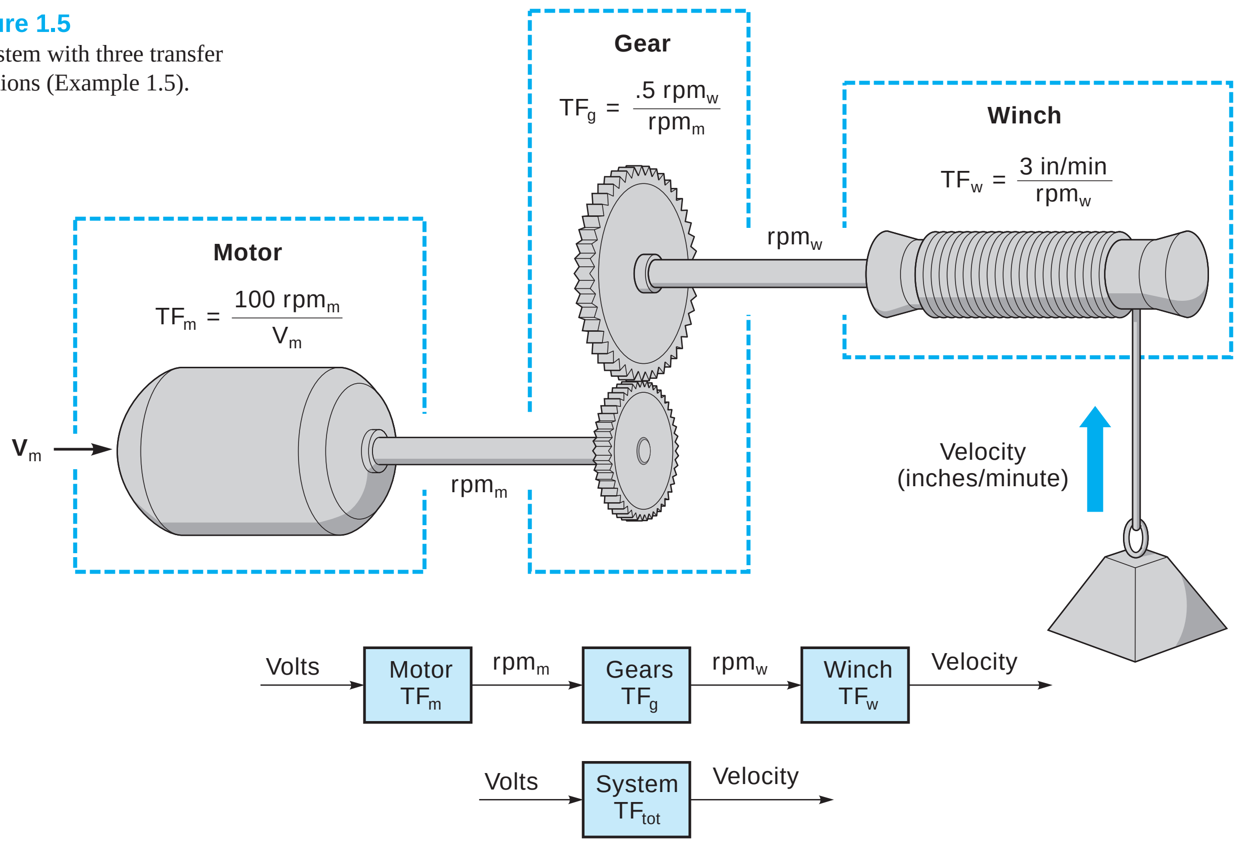


Figure 1.5
A system with three transfer functions (Example 1.5).

$$TF_{tot} = TF_m \times TF_g \times TF_w$$

$$= \frac{100\ \cancel{rpm}_m}{1\ V_m} \times \frac{0.5\ \cancel{rpm}_w}{1\ \cancel{rpm}_m} \times \frac{3\ in./min}{1\ \cancel{rpm}_w}$$

$$= 150\ in./min/V_m$$

We have shown that the transfer function of the complete system is 150 in./min/V_m. *Knowing this value, we can calculate the system output for any system input.* For example, if the input to the this system is 12 V (to the motor), the output speed of the winch is calculated as follows:

$$\text{Output} = \text{input} \times TF = \frac{12\ V \times 150\ in./min}{1\ V_m} = 1800\ in./min$$

1.2 ANALOG AND DIGITAL CONTROL SYSTEMS

In an **analog control system,** the controller consists of traditional analog devices and circuits, that is, linear amplifiers. The first control systems were analog because it was the only available technology. In the analog control system, any change in either set point or feedback is sensed immediately, and the amplifiers adjust their output (to the actuator) accordingly.

In a **digital control system,** the controller uses a digital circuit. In most cases, this circuit is actually a computer, usually microprocessor- or microcontroller-based. The computer executes a program that repeats over-and-over (each repetition is called an **iteration** or **scan**). The program instructs the computer to read the set point and sensor data and then use these numbers to calculate the controller output (which is sent to the actuator). The program then loops back to the beginning and starts over again. The total time for one pass through the program may be less than 1 millisecond (ms). The digital system only "looks" at the inputs at a certain time in the scan and gives the updated output later. If an input changes just after the computer looked at it, that change will remain undetected until the next time through the scan. This is fundamentally different than the analog system, which is continuous and responds immediately to any changes. However, for most digital control systems, the scan time is so short compared with the response time of the process being controlled that, for all practical purposes, the controller response is instantaneous.

The physical world is basically an "analog place." Natural events take time to happen, and they usually move in a continuous fashion from one position to the next. Therefore, most control systems are controlling analog processes. This means that, in many cases, the digital control system must first convert real-world analog input data into digital form before it can be used. Similarly, the output from the digital controller must be converted from digital form back into analog form. Figure 1.6 shows a block diagram of a digital closed-loop control system. Notice the two additional blocks: the

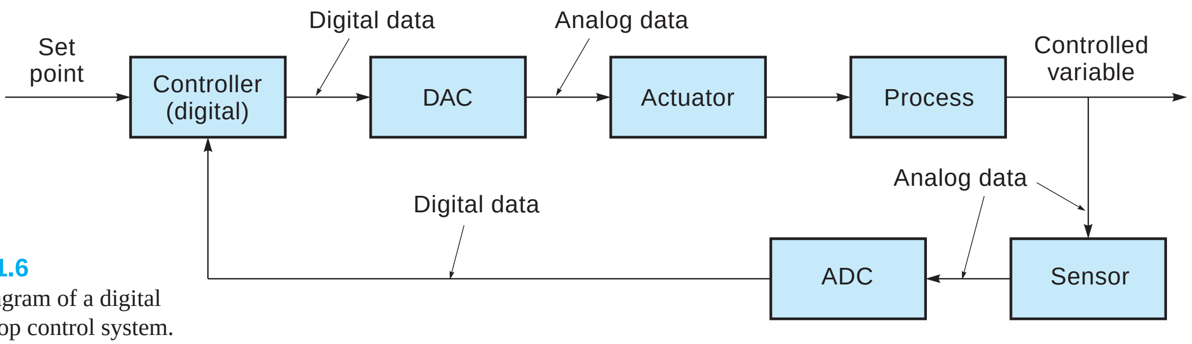


Figure 1.6
Block diagram of a digital closed-loop control system. (*Note:* A digital actuator, such as a stepper motor, would not need a DAC; similarly, a digital sensor, such as an optical shaft encoder, would not need an ADC.)

digital-to-analog converter (DAC) and the analog-to-digital converter (ADC). (These devices, which convert data between the digital and analog formats, are discussed in Chapter 2.) Also note that the feedback line is shown going directly into the controller. This emphasizes the fact that the computer, not a separate subtraction circuit, makes the comparison between the set point and the feedback signal.

1.3 CLASSIFICATIONS OF CONTROL SYSTEMS

So far we have discussed control systems as being either open or closed loop, analog or digital. Yet we can classify control systems in other ways, which have to do with applications. Some of the most common applications are discussed next.

Process Control

Process control refers to a control system that oversees some industrial process so that a uniform, correct output is maintained. It does this by monitoring and adjusting the control parameters (such as temperature or flow rate) to ensure that the output product remains as it should.

The classic example of process control is a closed-loop system maintaining a specified temperature in an electric oven, as illustrated in Figure 1.7. In this case, the actuator is the heating element, the controlled variable is the temperature, and the sensor is a thermocouple (a device that converts temperature into voltage). The controller regulates power to the heating element in such a way as to keep the temperature (as reported by the thermocouple) at the value specified by the set point.

Another example of process control is a paint factory in which two colors, blue and yellow, are mixed to produce green (Figure 1.8). To keep the output color constant, the exact proportions of blue and yellow must be maintained. The setup illustrated in Figure 1.8(a) accomplishes this with flow valves 1 and 2, which are manually adjusted until the desired hue of green is achieved. The problem is that, as the level of paint in the vats changes, the flow will change and the mixture will not remain constant.

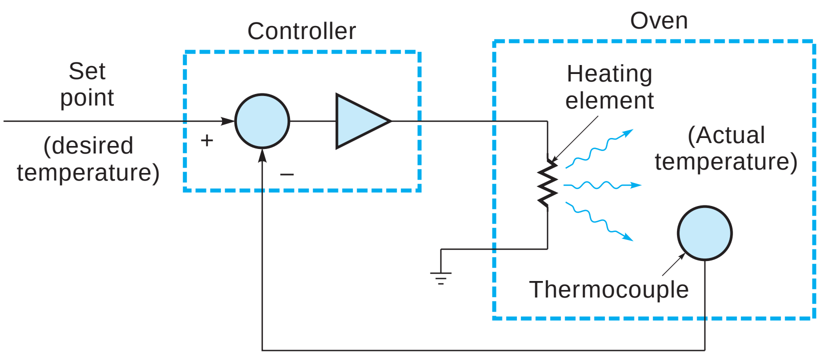


Figure 1.7
A closed-loop oven-heating system.

To maintain an even flow from the vats, we could add two electrically operated flow valves (and their controls) as shown in Figure 1.8(b). Each valve would maintain a specified flow of paint into the mixer, regardless of the upstream pressure. Theoretically, if the blue and yellow flows are independently maintained, the green should stay constant. In practice, however, other factors such as temperature or humidity may affect the mixing chemistry and therefore the output color.

A better approach might be the system shown in Figure 1.8(c); a single sensor monitors the output color. If the green darkens, the controller increases the flow of yellow. If the green gets too light, the flow of yellow is decreased. This system is desirable because it monitors the actual parameter that needs to be maintained. In real life, such a straightforward system may not be possible because sensors that can measure the output directly may not exist and/or the process may involve many variables.

Process control can be classified as being a batch process or a continuous process. In a **continuous process** there is a continuous flow of material or product, as in the paint-mixing example just described. A **batch process** has a beginning and an end (which is usually performed over and over). Examples of batch processes include mixing a batch of bread dough and loading boxes on a pallet.

In a large plant such as a refinery, many processes are occurring simultaneously and must be coordinated because the output of one process is the input of another. In the early days of process control, separate independent controllers were used for each process, as shown in Figure 1.9(a). The problem with this approach was that, to change the overall flow of the product, each controller had to be readjusted manually.

In the 1960s, a new system was developed in which all independent controllers were replaced by a single large computer. Illustrated in Figure 1.9(b), this system is called **direct digital control** (DDC). The advantage of this approach is that all local processes can be implemented, monitored, and adjusted from the same place. Also, because the computer can “see” the whole system, it is in a position to make adjustments to enhance total system performance. The drawback is that the whole plant is dependent on that one computer. If the computer goes off line to fix a problem in one process, the whole plant shuts down.

Figure 1.8
Process control in mixing paint.

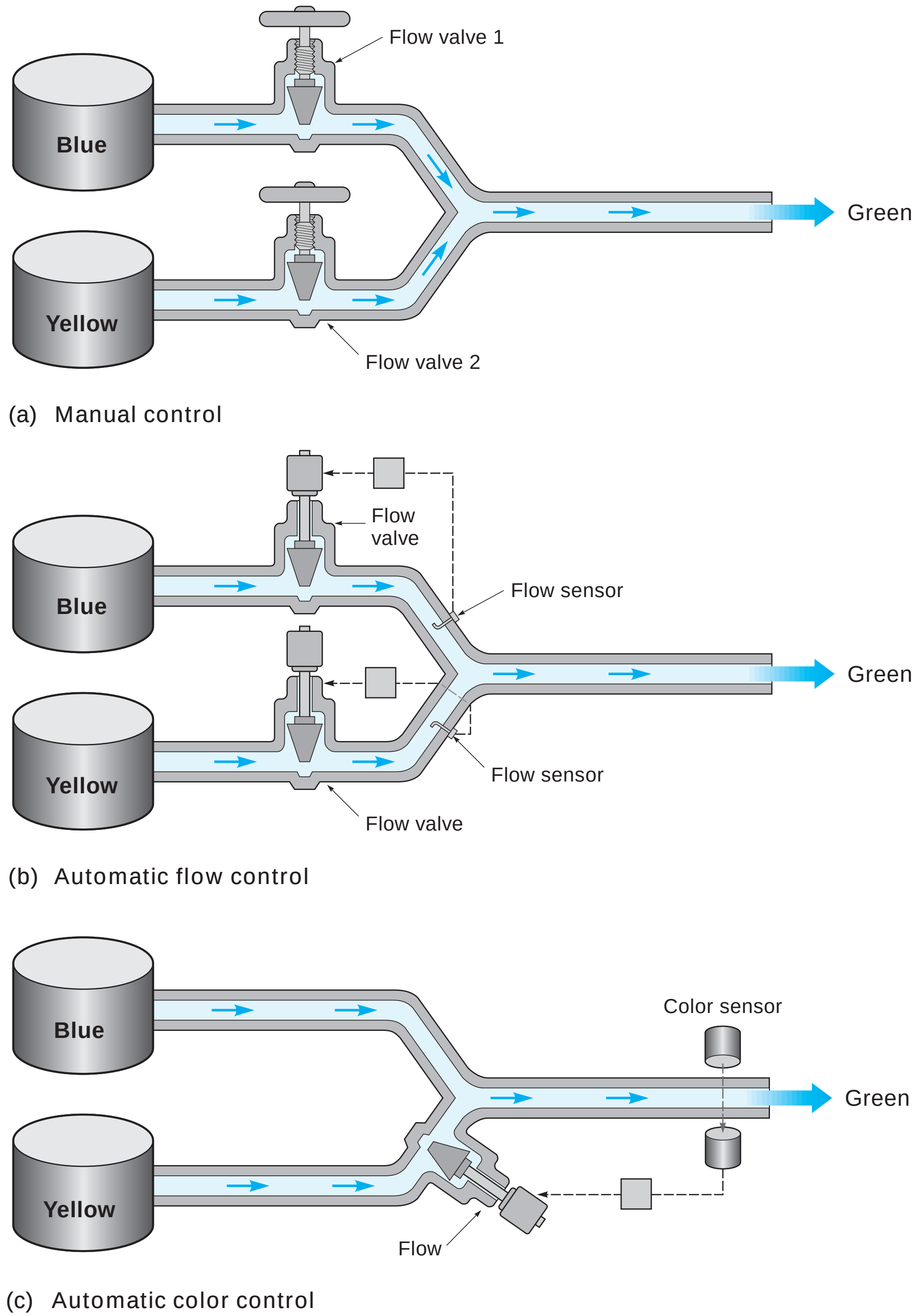
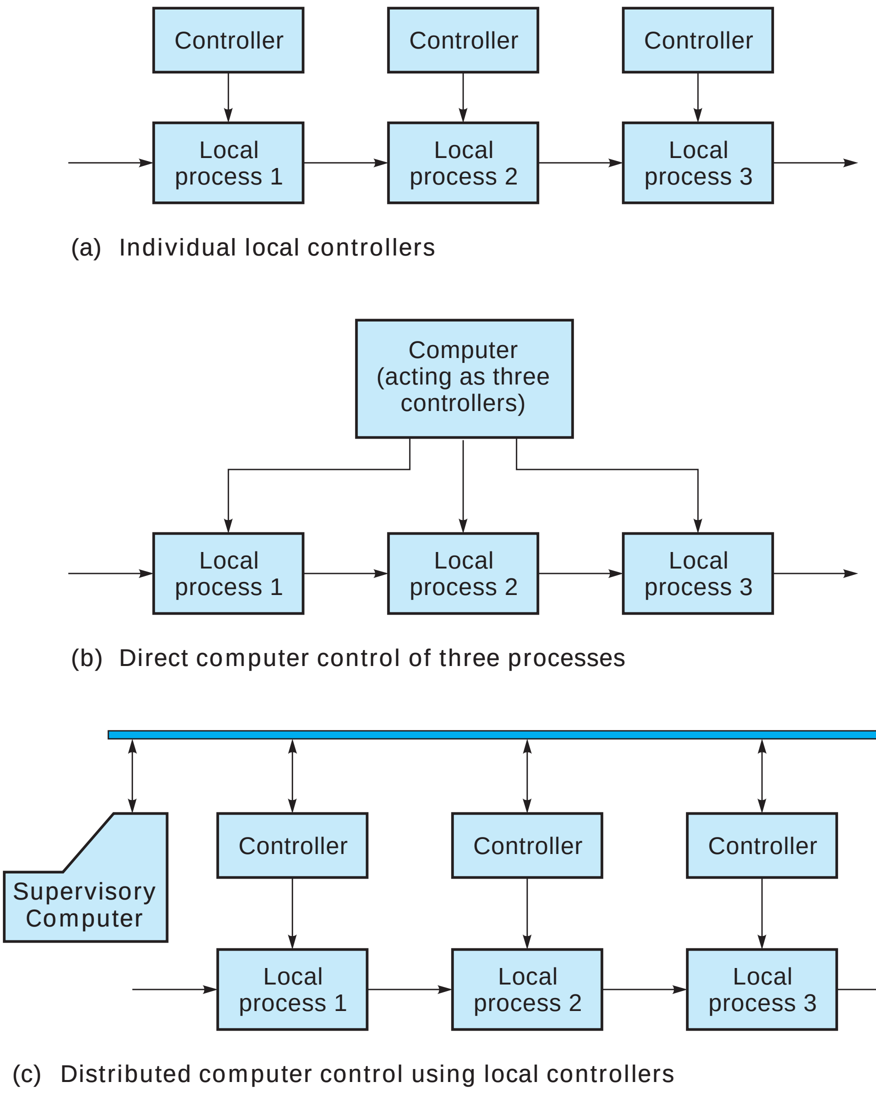


Figure 1.9
Approaches of multiprocess control.



The advent of small microprocessor-based controllers has led to a new approach called **distributed computer control** (DCC), illustrated in Figure 1.9(c). In this system, each process has its own separate controller located at the site. These local controllers are interconnected via a local area network so that all controllers on the network can be monitored or reprogrammed from a single supervisory computer. Once programmed, each process is essentially operating independently.

This makes for a more robust and safe system, because all the local processes will continue to function even if the supervisory computer or network goes down. For example, a local controller whose job it is to keep some material at a critical temperature will continue to function even if the supervisory computer is temporarly disabled.

Increasingly, the components of a control system are being interconnected with the “business office” network in a factory, which allows the status of any process in the factory to be examined by any computer on anyone’s desk. You might be able to sit down at a PC anywhere in the building and determine whether a particular photo sensor on an assembly line has a dirty lens or how much current a particular motor is drawing.

Sequentially Controlled Systems

A **sequentially controlled system** controls a process that is defined as a series of tasks to be performed—that is, a sequence of operations, one after the other. Each operation in the sequence is performed either for a certain amount of time, in which case it is **time-driven,** or until the task is finished (as indicated by, say, a limit switch), in which case it is **event-driven.** A time-driven sequence is *open-loop* because there is no feedback, whereas an event-driven task is *closed-loop* because a feedback signal is required to specify when the task is finished.

The classic example of a sequentially controlled system is the automatic washing machine. The first event in the wash cycle is to fill the tub. This is an event-driven task because the water is admitted until it gets to the proper level as indicated by a float and limit switch (closed loop). The next two tasks, wash and spin-drain, are each done for a specified period of time and are time-driven events (open loop). A timing diagram for a washing machine is shown in Figure 1.10.

Another example of a sequentially controlled system is a traffic signal. The basic sequence may be time-driven: 45 seconds for green, 3 seconds for yellow, and 45 seconds for red. The presence or absence of traffic, as indicated by sensors in the roadbed, however, may alter the basic sequence, which is an event-driven control.

Many automated industrial processes could be classified as sequentially controlled systems. An example is a process where parts are loaded into trays, inserted into a furnace for 10 minutes, then removed and cooled for 10 minutes, and loaded into boxes in groups of six. In the past, most sequentially controlled systems used switches, relays, and electromechanical timers to implement the control logic. These tasks are now performed

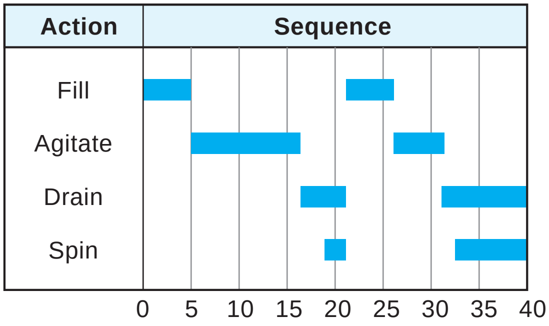


Figure 1.10
Timing diagram for an automatic washing machine.

more and more by small computers known as **programmable logic controllers** (PLCs), which are less expensive, more reliable, and easily reprogrammed to meet changing needs—for example, to put eight items in a box instead of six. (PLCs are discussed in Chapter 12.)

Motion Control

Motion control is a broad term used to describe an open-loop or closed-loop electromechanical system wherein things are moving. Such a system typically includes a motor, mechanical parts that move, and (in many cases) feedback sensor(s). Automatic assembling machines, industrial robots, and numerical control machines are examples.

Servomechanisms

Servomechanism is the traditional term applied to describe a closed-loop electromechanical control system that directs the precise movement of a physical object such as a radar antenna or robot arm. Typically, either the output position or the output velocity (or both) is controlled. An example of a servomechanism is the positioning system for a radar antenna, as shown in Figure 1.11. In this case, the controlled variable is the antenna position. The antenna is rotated with an electric motor connected to the controller located some distance away. The user selects a direction, and the controller directs the antenna to rotate to a specific position.

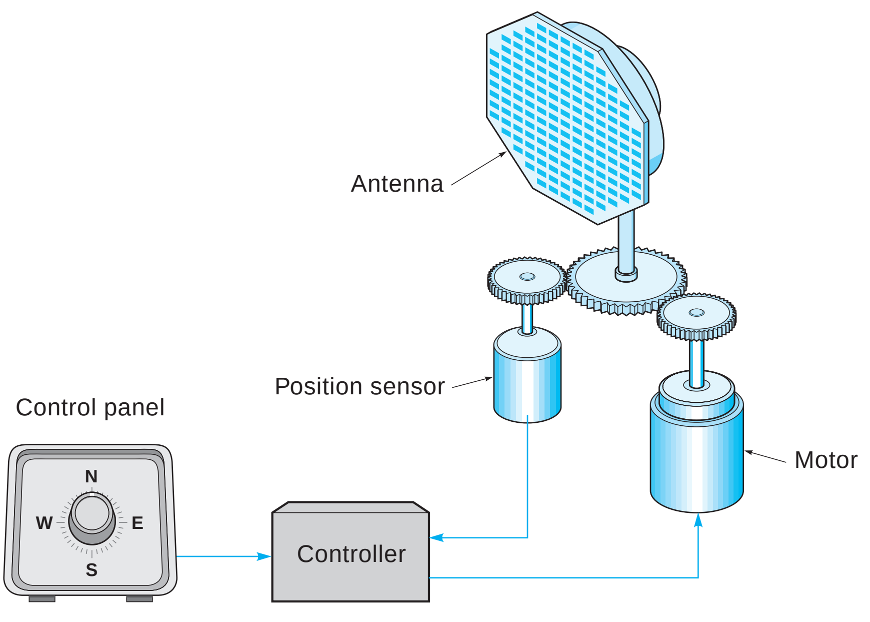


Figure 1.11
A servomechanism: a remote antenna-positioning system.

Numerical Control

Numerical control (NC) is the type of digital control used on machine tools such as lathes and milling machines. These machines can automatically cut and shape the workpiece without a human operator. Each machine has its own set of axes or parameters that must be controlled; as an example, consider the milling machine shown in Figure 1.12. The workpiece that is being formed is fastened to a movable table. The table can be moved (with electric motors) in three directions: *X*, *Y*, and *Z*. The cutting-tool speed is automatically controlled as well. To make a part, the table moves the workpiece past the cutting tool at a specified velocity and cutting depth. In this example, four parameters (*X*, *Y*, *Z*, and rpm) are continuously and independently controlled by the controller. The controller takes as its input a series of numbers that completely describe how the part is to be made. These numbers include the physical dimensions and such details as cutting speeds and feed rates.

NC machines have been used since the 1960s, and certain standards that are unique to this application have evolved. Traditionally, data from the part drawing were

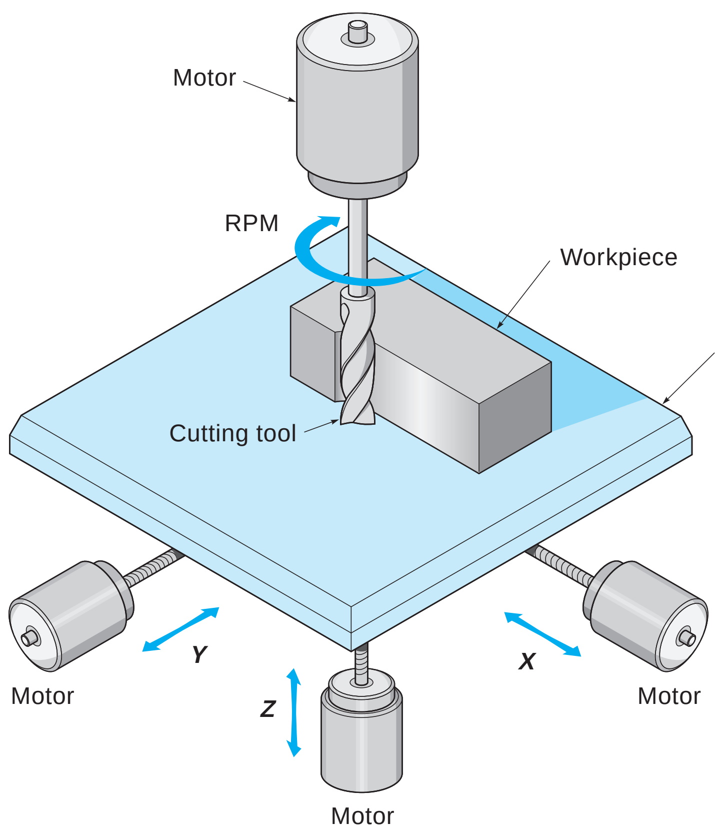


Figure 1.12
Basics of a numerical-control milling machine.

entered manually into a computer program. This program converted the input data into a series of numbers and instructions that the NC controller could understand, and either stored them on a floppy disk or tape, or sent the data directly to the machine tool. These data were read by the machine-tool controller as the part was being made. With the advent of **computer-aided design** (CAD), the job of manually programming the manufacturing instructions has been eliminated. Now it is possible for a special computer program (called a *postprocessor*) to read the CAD-generated drawing and then produce the necessary instructions for the NC machine to make the part. This whole process—from CAD to finished part—is called **computer-aided manufacturing** (CAM).

One big advantage of this process is that one machine tool can efficiently make many different parts, one after the other. This system tends to reduce the need for a large parts inventory. If the input tape (or software) is available, any needed part can be made in a short period of time. This is one example of **computer-integrated manufacturing** (CIM), a whole new way of doing things in the manufacturing industry. CIM involves using the computer in every step of the manufacturing operation—from the customer order, to ordering the raw materials, to machining the part, to routing it to its final destination.

Robotics

Industrial **robots** are classic examples of position control systems. In most cases, the robot has a single arm with shoulder, elbow, and wrist joints, as well as some kind of hand known as an *end effector*. The end effector is either a gripper or other tool such

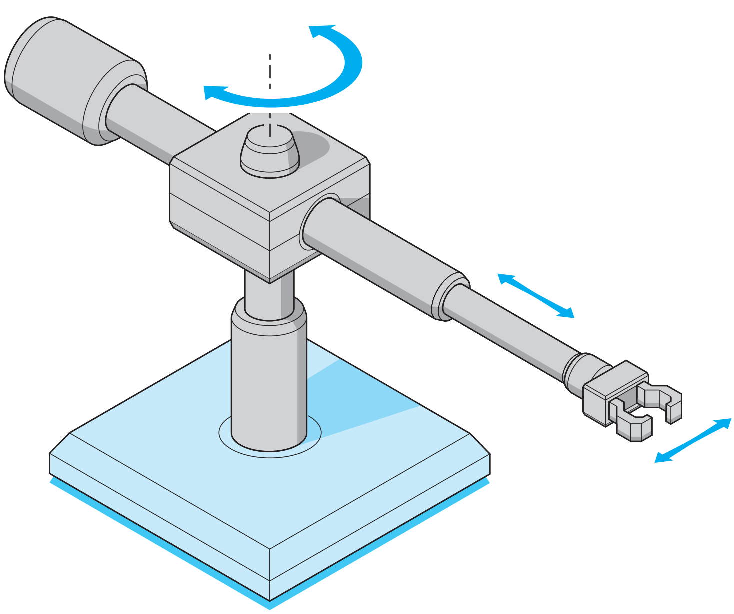


Figure 1.13
A pick-and-place robot.

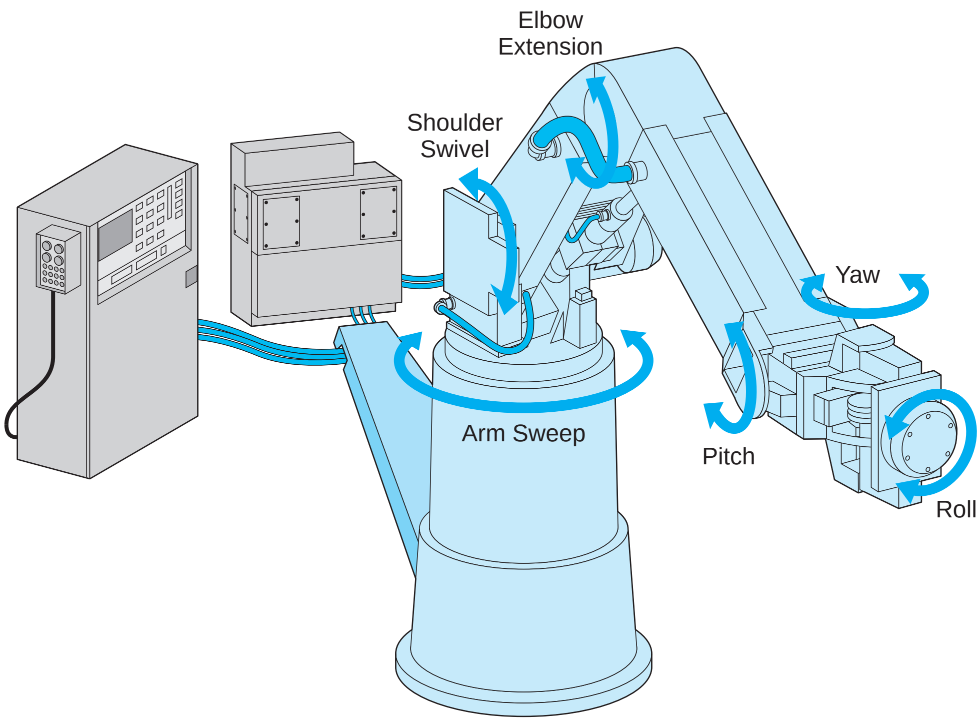


Figure 1.14
A large industrial robot.

as a paint spray gun. Robots are used to move parts from place to place, assemble parts, load and off-load NC machines, and perform such tasks as spray painting and welding.

Pick-and-place robots, the simplest type, pick up parts and place them somewhere else nearby. Instead of using sophisticated feedback control, they are often run open-loop using mechanical stops or limit switches (discussed in Chapter 4) to determine how far in each direction to go (sometimes called a "bang-bang" system). An example is shown in Figure 1.13. This robot uses pneumatic cylinders to lift, rotate, and extend the arm. It can be programmed to repeat a simple sequence of operations.

Sophisticated robots use closed-loop position systems for all joints. An example is the industrial robot shown in Figure 1.14. It has six independently controlled axes (known as six degrees of freedom) allowing it to get to difficult-to-reach places. The robot comes with and is controlled by a dedicated computer-based controller. This unit is also capable of translating human instructions into the robot program during the "teaching" phase. The arm can move from point to point at a specified velocity and arrive within a few thousandths of an inch.

SUMMARY

A control system is a system where electronic intelligence controls some physical process. This text will deal with all phases of the control system: the electronics, the power sources (such as motors), the mechanics, and control system theory, which ties together all the concepts.

A control system is described in terms of a block diagram. The first block is the controller, which represents the electronic intelligence. The controller outputs a control signal to the next block, which is the actuator. The actuator is the system's first physical device to do something (for example, a motor or heating element).

There are two general categories of control systems: open loop and closed loop. In open-loop control, the controller sends a measured signal, specifying the desired action, to the actuator (the controller, however, has no way of knowing what the actuator actually does). Closed-loop control includes a sensor that feeds back a signal from the actuator to the controller, informing the controller exactly what the output is doing. This allows the controller to make correctional adjustments.

Each component in the control system can be described mathematically by a transfer function (TF), where TF = output/input. Transfer functions of individual components in a system can be mathematically combined to calculate overall system performance. A true transfer function includes time-dependent and steady-state characteristics, whereas a useful simplification (employed in this text) considers only steady-state conditions.

Control systems are classified as analog or digital. In an analog control system, the controller uses traditional analog electronic circuits such as linear amplifiers. In a digital control system, the controller uses a digital circuit, usually a computer.

Control systems are classified by application. Process control usually refers to an industrial process being electronically controlled for the purpose of maintaining a uniform correct output. Motion control refers to a system wherein things move. A servomechanism is a feedback control system that provides remote control motion of some object, such as a robot arm or a radar antenna. A numerical control (NC) control system directs a machine tool, such as a lathe, to machine a part automatically.

GLOSSARY

actuator The first component in the control system which generates physical movement, typically a motor. The actuator gets its instructions directly from the controller. Another name for the actuator is the *final control element*

analog control system A control system where the controller is based on analog electronic circuits, that is, linear amplifiers.

batch process A process that has a beginning and an end and is usually preformed over and over.

CAD See **computer-aided design.**

CAM See **computer-aided manufacturing.**

CIM See **computer-integrated manufacturing.**

closed-loop control system A control system that uses feedback. A sensor continually monitors the output of the system and sends a signal to the controller, which makes adjustments to keep the output within specification.

comparator Part of the control system that subtracts the feedback signal (as reported by the sensor) from the set point, to determine the error.

computer-aided design A computer system that makes engineering drawings.

computer-aided manufacturing A computer system that allows CAD drawings to be converted for use by a numerical control (NC) machine tool.

computer-integrated manufacturing A computer system that oversees every step in the manufacturing process, from customer order to delivery of finished parts.

continuous process A process wherein there is a continuous flow of product—for example, a steam boiler where water is continuously pumped in and steam continuously comes out.

controlled variable The ultimate output of the process; the actual parameter of the process that is being controlled.

controller The machine intelligence of the control system.

control strategy The set of rules that the controller follows to determine its output to the actuator.

control system A system that may include electronic and mechanical components, where some type of machine intelligence controls a physical process.

DCC See **distributed computer control.**

DDC See **direct digital control.**

digital control system A control system where the controller is a digital circuit, typically a computer.

direct digital control An approach to process control where all controllers in a large process are simulated by a single computer.

distributed computer control An approach to process control where each process has its own local controller, but all individual controllers are connected to a single computer for programming and monitoring.

error In a control system, the difference between where the system is supposed to be (set point) and where it really is.

event control system A control system that cycles through a predetermined series of steps.

event-driven operation In a sequentially controlled system, an action that is allowed to start or continue based on some parameter changes. This is an example of closed-loop control.

feedback The signal from the sensor, which is fed back to the controller.

follow-up system A control system where the output follows a specified path.

forward path The signal-flow direction of the controller to the actuator.

gain The steady-state relationship between input and output of a component. (In this text, *gain* and *transfer function* are used interchangeably, although this is a simplification.)

iteration See **scan.**

motion control A term that refers to an electromechanical system wherein things move.

NC See **numerical control.**

numerical control A digital control system that directs machine tools, such as a lathe, to automatically machine a part.

open-loop control system A control system that does not use feedback. The controller sends a measured signal to the actuator, which specifies the desired action. This type of system is *not* self-correcting.

pick-and-place robot A simple robot that does a repetitive task of picking up and placing an object somewhere else.

PLC See **programmable logic controller.**

programmable logic controller A small, self-contained microprocessor-based controller used primarily to replace relay logic controllers.

process The physical process that is being controlled.

process control A control system that maintains a uniform, correct output for some industrial process.

regulator system A control system that maintains an output at a constant value.

robot A servomechanism type control system in the form of a machine with a movable arm.

scan One cycle through the program loop of a computer-based controller.

sensor Part of the control system that monitors the system output, the sensor converts the physical output action of the system into an electric signal, which is fed back to the controller.

sequentially controlled system A control system that performs a series of actions in sequence, an example being a washing machine.

servomechanism An electromechanical feedback control system where the output is linear or rotational movement of a mechanical part.

set point The input signal to the control system, specifying the desired system output.

time-driven operation In a sequentially controlled system, an action that is allowed to happen for a specified period of time. This is an example of open-loop control.

TF See **transfer function.**

transfer function A mathematical relationship between the input and output of a control system component: TF = output/input. (In this text, *transfer function* and *gain* are used interchangeably, although this is a simplification.)

EXERCISES

Section 1.1

1. **a.** Draw a block diagram of an open-loop control system.
b. Use the block diagram to describe how the system works.
c. What basic requirements must the components meet for this system to work?
d. What is the advantage of this system over a closed-loop system?

2. **a.** Draw a block diagram of a closed-loop control system.
b. Use the block diagram to describe how the system works.
c. What is the advantage of this system over an open-loop system?

3. The controlled variable in a closed-loop system is a robot arm. Initially, it is at 45°; then it is commanded to go to 30°. Describe what happens in terms of set point, feedback signal, error signal, and arm position.

4. Identify the following as open- or closed-loop control.
a. Controlling the water height in a toilet tank
b. Actuation of street lights at 6 P.M.
c. Stopping a clothes dryer when the clothes are dry
d. Actuation of an ice maker when the supply of cubes is low

5. A potentiometer has a transfer function of 0.1 V/deg. Find the pot's output if the input is 45°.

6. A potentiometer has a transfer function of 0.05 V/deg. Find the pot's output if the input is 89°.

7. A motor was measured to rotate (unloaded) at 500 rpm with a 6-V input and 1000 rpm with a 12-V input. What is the transfer function (steady state) for the unloaded motor?

8. In a certain system, an electric heating element was found to increase the temperature of a piece of metal 10° for each ampere of current. The metal expands 0.001 in./deg and pushes on a load sensor which outputs 1 V/0.005 in. of compression.

- **a.** Find the transfer functions of the three components and draw the block diagram.
- **b.** Calculate the overall transfer function of this system.

Section 1.2

9. Describe the differences between an *analog* and a *digital control system*

10. The iteration time of a digital controller is 1 s. Would this controller be appropriate for the following?
- **a.** A robot that paint sprays cars
- **b.** A solar panel control system that tracks the sun across the sky

Section 1.3

11. What is the difference between a *process control system* and a *servomechanism*

12. What is the difference between *direct digital control* and *distributed computer control*

13. Give an example (other than in this book) of the following:
- **a.** A time-driven control system
- **b.** An event-driven control system
- **c.** A combined time- and event-driven control system

14. Give an example (other than in this book) of a servomechanism.