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Devices, Systems & Applications

3rd Edition

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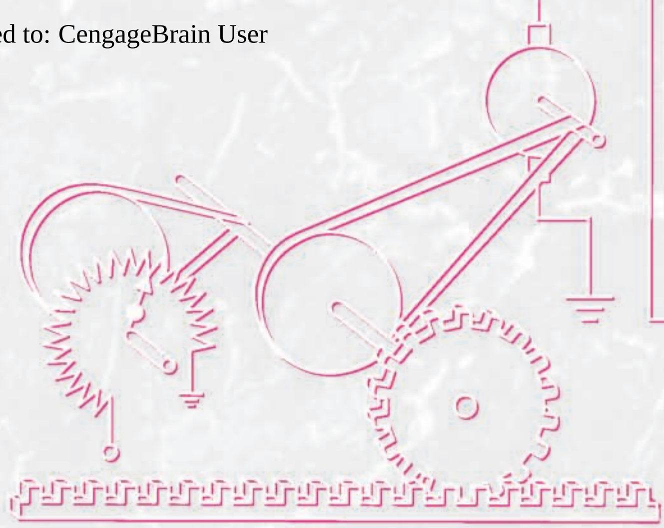


SECTION 1

Industrial Control Overview

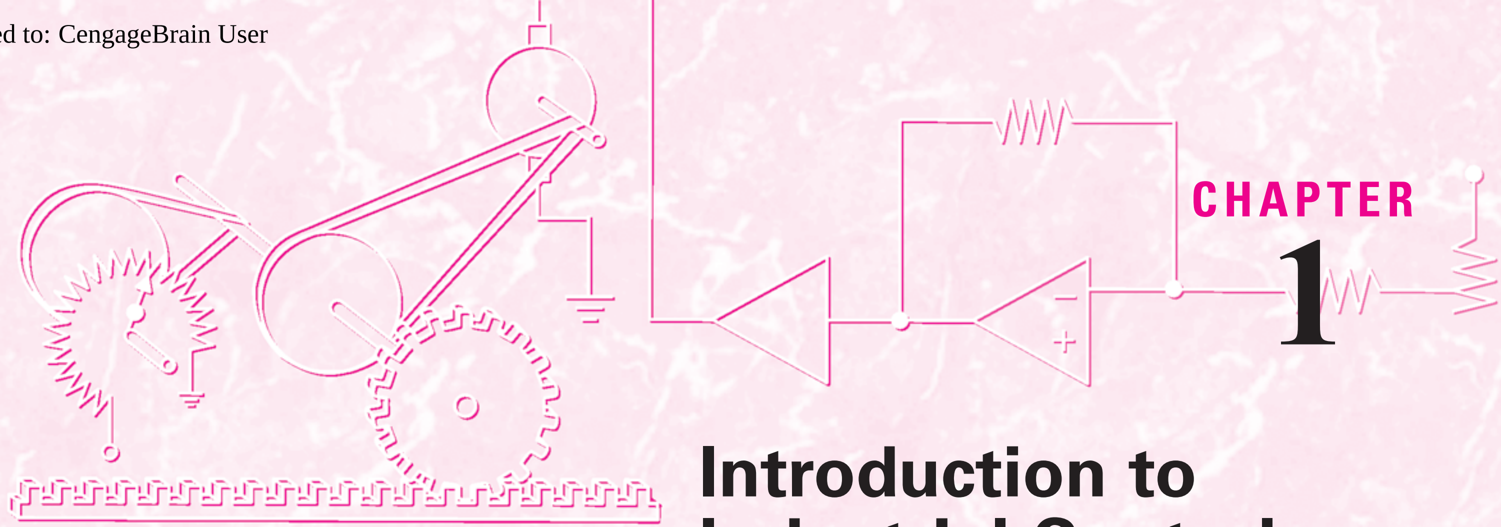
OUTLINE

Section one introduces key concepts in industrial control. The first chapter introduces the student to the ways in which industrial control systems are classified. It then provides an introductory overview of the elements that make up an industrial control loop.

Chapter 2 describes the operation of discrete components and integrated circuits that are used throughout the book.

Chapter 3 covers thyristor devices and circuits that provide power to actuators of a closed-loop system.

The remaining sections describe each element of a control loop in detail so that the entire spectrum of industrial control is addressed.



CHAPTER 1

Introduction to Industrial Control Systems

OBJECTIVES

At the conclusion of this chapter, you should be able to:

- List the classifications of industrial control systems.
- Describe the differences between the different industrial control systems and provide examples of each type.
- Define the following terms associated with industrial control systems:

Servos	Batch	Instrumentation
Servomechanisms	Continuous	

- Describe the differences between open-loop and closed-loop systems.
- Define the following terms associated with open- and closed-loop systems:

Negative Feedback	Error Detector	Disturbance
Controlled Variable	Error Signal	Measured Variable
Measurement Device	Controller	Manipulated Variable
Feedback Signal	Actuator	Controller Output Signal
Set Point	Manufacturing Process	

- List the factors that affect the dynamic response of a closed-loop system.
- Describe the operation of Feed-Forward Control.
- List three factors that cause the controlled variable to differ from the set point.

INTRODUCTION

The industrial revolution began in England during the mid-1700s when it was discovered that productivity of spinning wheels and weaving machines could be dramatically increased by fitting them with steam-powered engines. Further inventions and new ideas in plant layouts during the 1850s enabled the United States to surpass England as the manufacturing leader of the world. Around the turn of the twentieth century, the electric motor replaced steam and water wheels as a power source. Factories became larger, machines were improved to allow closer tolerances, and the assembly line method of mass production was created.

Between World Wars I and II, the feedback control system was developed, enabling manually operated machines to be replaced by automated equipment. The feedback control system is a key element in today's manufacturing operations. The term **industrial controls** is used to define this type of system, which automatically monitors manufacturing processes being executed and takes appropriate corrective action if the operation is not performing properly.

During World War II, significant advances in feedback technology occurred due to the sophisticated control systems required by military weapons. After the war, the techniques used in military equipment were applied to industrial controls to further improve the quality of products and to increase productivity.

Because many modern factory machines are automated, the technicians who install, troubleshoot, and repair them need to be highly trained. To perform effectively, these individuals must understand the elements, operational theory, and terminology associated with industrial control systems.

Industrial control theory encompasses many fields, but uses the same basic principles whether controlling the position of an object, the speed of a motor, or the temperature and pressure of a manufacturing process.

In this chapter, the various types of industrial control systems, their characteristics, and important terminology will be studied.

1-1 Industrial Control Classifications

Motion and Process Controls

Industrial control systems are often classified by *what* they control: either motion or process.

Motion Control

A **motion control** system is an automatic control system that controls the physical motion or position of an object. One example is the industrial robot arm which performs welding operations and assembly procedures.

There are three characteristics that are common to all motion control systems. First, motion control devices control the position, speed, acceleration, or deceleration of a mechanical object. Second, the motion or position of the object being controlled is measured. Third, motion devices typically respond to input commands within fractions of a second, rather than seconds or minutes, as in process control. Hence, motion control systems are faster than process control systems.

Motion control systems are also referred to as *servos,* or *servomechanisms.* Other examples of motion control applications are CNC machine tool equipment, printing presses, office copiers, packaging equipment, and electronics parts insertion machines that place components onto a printed circuit board.

Process Control

The other type of industrial control system is **process control.** In process control, one or more variables are regulated during the manufacturing of a product. These variables may include temperature, pressure, flow rate, liquid and solid level, pH, or humidity. This regulated process must compensate for any outside disturbance that changes the variable. The response time of a process control system is typically slow, and can vary from a few seconds to several minutes. Process control is the type of industrial control system most often used in manufacturing. Process control systems are divided into two categories, *batch* and *continuous.*

Batch Process **Batch processing** is a sequence of timed operations executed on the product being manufactured. An example is an industrial machine that produces various types of cookies, as shown in Figure 1-1. Suppose that chocolate-chip cookies are made in the first production run. First, the oven is turned on to the desired temperature. Next, the required ingredients in proper quantities are dispensed into the sealed mixing chamber. A large blender then begins to mix the contents.

After a few minutes, vanilla is added, and the mixing process continues. After a prescribed period of time, the dough is the proper consistency, the blender stops turning, and the compressor turns on to force air into the mixing chamber. When the air pressure reaches

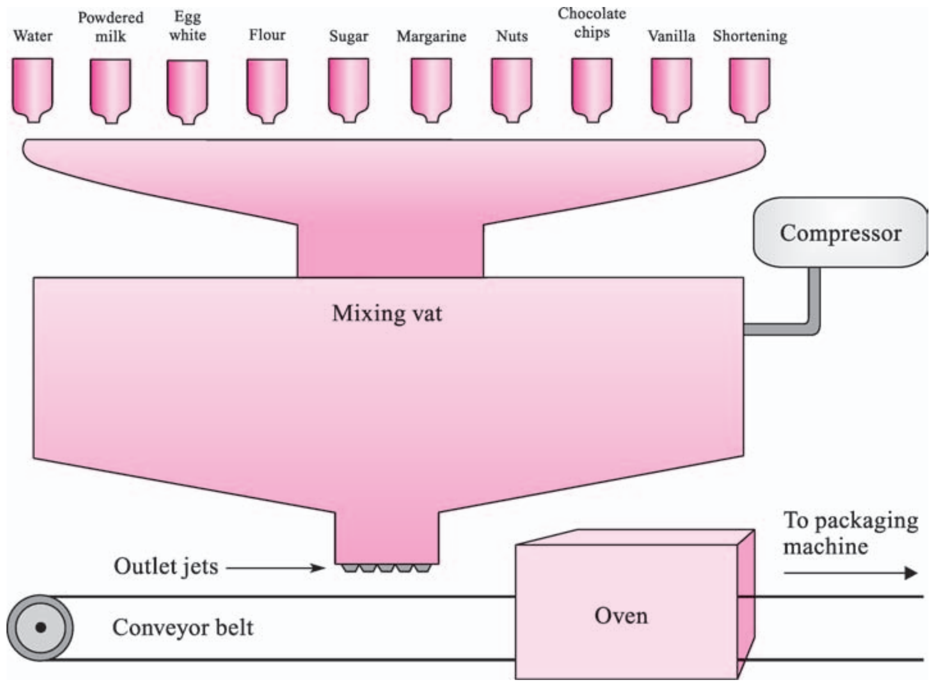


FIGURE 1-1 Batch processing cookie machine

a certain point, the conveyor belt turns on. The pressurized air forces the dough through outlet jets onto the belt. The dough balls become fully baked as they pass through the oven. The cookies cool as the belt carries them to the packaging machine.

After the packaging step is completed, the mixing vat, blender, and conveyor belt are washed before a batch of raisin-oatmeal cookies is made. Products from foods to petroleum to soap to medicines are made from a mixture of ingredients that undergo a similar batch process operation.

Batch process is also known as *sequence* (or *sequential*) *process.*

Continuous Process In the **continuous process** category, one or more operations are being performed as the product is being passed through a process. Raw materials are continuously entering and leaving each process step. Producing paper, as shown in Figure 1-2, is an example of continuous process. Water, temperature, and speed are constantly monitored and regulated as the pulp is placed on screens, fed through rollers, and gradually transformed into a finished paper product. The continuous process can last for hours, days, or even weeks without interruption. Everything from wire to textiles to plastic bags is manufactured by using a continuous manufacturing process similar to the paper machine.

Other examples of continuous process control applications are wastewater treatment, nuclear power production, oil refining, and natural gas distribution through pipe lines.

Another term commonly used instead of process control is *instrumentation.*

The primary difference between process and motion control is the control method that is required. In process control, the emphasis is placed on sustaining a constant condition of a parameter, such as level, pressure, or flow rate of a liquid. In servo control, the input command is constantly changing. The emphasis of the system is to follow the changes in the desired input signal as closely as possible. Variations of the input signal are typically very rapid.

Open- and Closed-Loop Systems

The purpose of any industrial system is to maintain one or more variables in a production process at a desired value. These variables include pressures, temperatures, fluid levels, flow rates, composition of materials, motor speeds, and positions of a robotic arm.

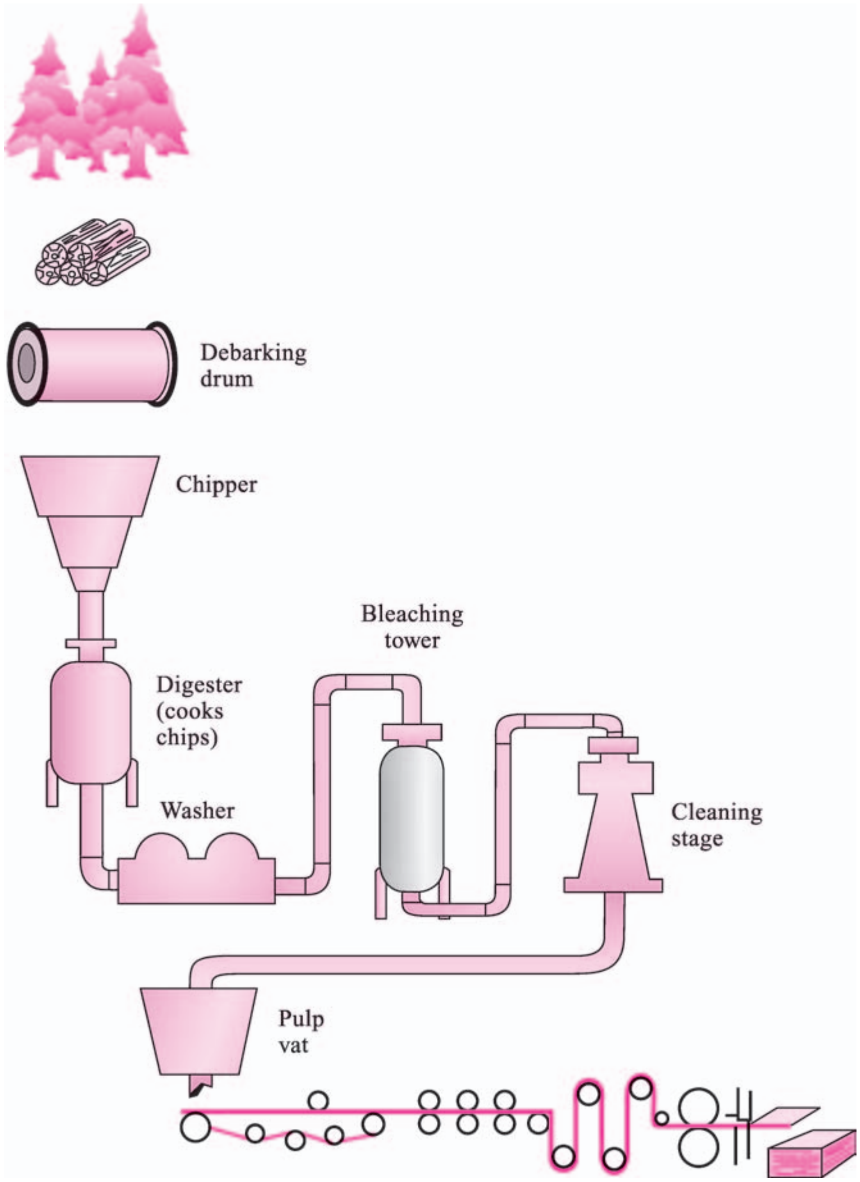


FIGURE 1-2 A pulp and paper operation is a process control application

Industrial control systems are also classified by how they control variables, either manually in an **open-loop** system or automatically in a **closed-loop** system.

Open-Loop Systems

An open-loop system is the simplest way to control a system. A tank that supplies water for an irrigation system can be used to illustrate an open-loop (or manual control) system. The diagram in Figure 1-3 shows a system composed of a storage tank, an inlet pipe with a manual control valve, and an outlet pipe. A continuous flow of water from a natural spring enters the tank at the inlet, and water flows from the outlet pipe to the irrigation system. The process variable that is maintained in the tank is the water level. Ideally, the manual flow control valve setting and the size of the outlet pipe are exactly the same. When this occurs, the water level in the tank remains the same. Therefore the process reaches a steady-state condition, or is said to be *balanced.* The problem with this design is that any change or disturbance will upset the balance. For example, a substantial rainfall may occur, causing additional water to enter the storage tank from the top. Since there is more water entering the

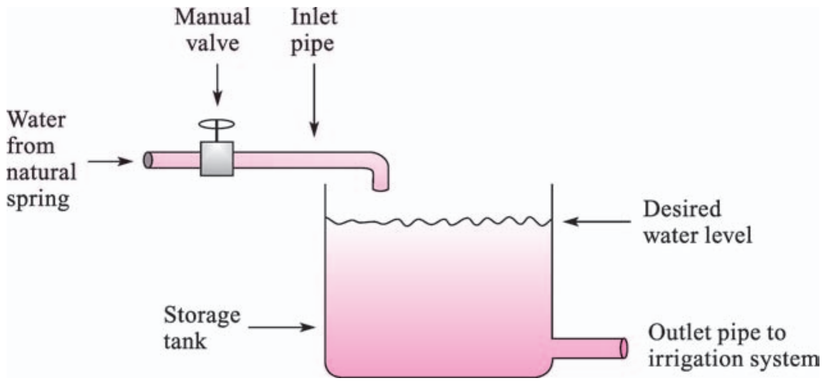


FIGURE 1-3 An open-loop reservoir system that stores water for an irrigation system

tank than exiting, the level will rise. If this situation is not corrected, the tank will eventually overflow. Excessive evaporation will also upset the balance. If it occurs over a prolonged period of time, the water level in the tank may become unacceptably low.

A human operator who periodically inspects the tank can change the control valve setting to compensate for these disturbances.

An example of a manually operated open-loop system is the speed of a car being controlled by the driver. The driver adjusts the throttle to maintain a highway speed when going uphill, downhill, or on level terrain.

Closed-Loop Systems

There are many situations in industry where the open-loop system is adequate. However, some manufacturing applications require continuous monitoring and self-correcting action of the operation for long periods of time without interruption. The automatic closed-loop configuration performs the self-correcting function. This automatic system employs a feedback loop to keep track of how closely the system is doing the job it was commanded to do.

The reservoir system can also be used to illustrate a closed-loop operation. To perform automatic control, the system is modified by replacing the manually controlled valve with an adjustable valve connected to a float, as shown in Figure 1-4. The valve, the float, and the linkage mechanism provide the feedback loop.

If the level of the water in the tank goes up, the float is pushed upward; if the level goes down, the float moves downward. The float is connected to the inlet valve by a mechanical linkage. As the water level rises, the float moves upward, pushing on the lever and closing the valve, thus reducing the water flow into the tank. If the water level lowers, the float moves

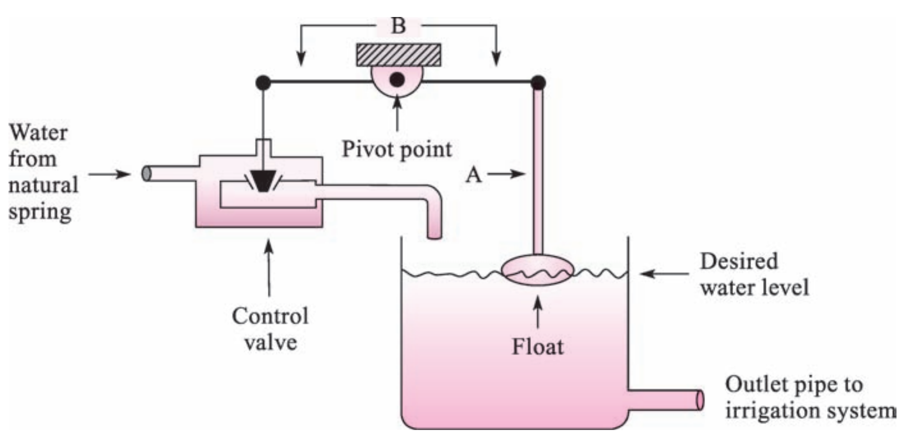


FIGURE 1-4 A closed-loop system that uses a linkage mechanism as a feedback device to provide self-correcting capabilities

downward, pulling on the lever and opening the valve, thus admitting more water into the tank. To adjust for a desired level of water in the tank, the float is moved up or down on the float rod A.

Most automated manufacturing processes use closed-loop control. These systems that have a self-regulation capability are designed to produce continuous balance.

1-2 Elements of Open- and Closed-Loop Systems

A block diagram of a closed-loop control system is shown in Figure 1-5. Each block shows an element of the system that performs a significant function in the operation. The lines between the blocks show the input and output signals of each element, and the arrowheads indicate the direction in which they flow.

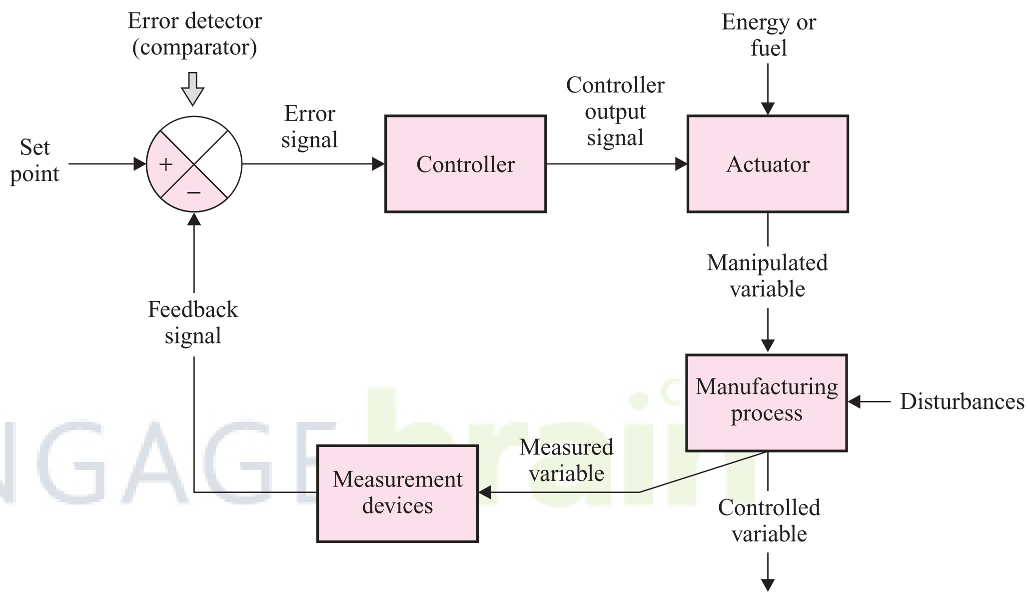


FIGURE 1-5 Closed-loop block diagram that shows elements, input/output signals, and signal direction

This section describes the functions of the blocks, their signals, and common terminology used in a typical closed-loop network:

Controlled Variable. The **controlled variable** is the actual variable being monitored and maintained at a desired value in the manufacturing process. Examples in a process control system may include temperature, pressure, and flow rate. Examples in a motion control system may be position or velocity. In the water reservoir system (Figure 1-4), the water level is the controlled variable. Another term used is *process variable.*

Measured Variable. To monitor the status of the controlled variable, it must be measured. Therefore, the condition of the controlled variable at a specific point in time is referred to as the **measured variable.** Various methods are used to make measurements. One method of determining a controlled variable such as the level of water, for example, is to measure the pressure at the bottom of a tank. The pressure that represents the controlled variable is taken at the instant of measurement.

Measurement Device. The **measurement device** is the "eye" of the system. It senses the measured variable and produces an output signal that represents the status of the controlled variable. Examples in a process control system may include a thermocouple to measure temperature or a humidity detector to measure moisture. Examples in a motion control system may be an optical device to measure position or a tachometer to measure rotational speed. In the water reservoir system, the float is the measurement device. Other terms used are *detector, transducer,* and *sensor.*

Feedback Signal. The **feedback signal** is the output of the measurement device. In the water reservoir system, the feedback signal is the vertical position of member A in the linkage mechanism (see Figure 1-4). Other terms used are *measured value, measurement signal,* or *position feedback* if in a position loop, or *velocity feedback* if in a velocity loop.

Set Point. The **set point** is the prescribed input value applied to the loop that indicates the desired condition of the controlled variable. The set point may be manually set by a human operator, automatically set by an electronic device, or programmed into a computer. In the water reservoir system, the set point is determined by the position at which the float is placed along rod A. Other terms used are *command,* or *reference.*

Error Detector. The error detector compares the set point to the feedback signal. It then produces an output signal that is proportional to the difference between them. In the water reservoir system, the error detector is the entire linkage mechanism. Other terms used are *comparator* or *comparer* and *summing junction.*

Error Signal. The **error signal** is the output of the error detector. If the set point and the feedback signal are not equal, an error signal proportional to their difference develops. When the feedback and set point signals are equal, the error signal goes to zero. In the reservoir system (Figure 1-4), the error signal is the angular position of member B of the linkage mechanism. Other terms used are *difference signal* and *deviation.*

Controller. The **controller** is the "brain" of the system. It receives the error signal (for closed-loop control) as its input, and develops an output signal that causes the controlled variable to become the value specified by the set point. Most controllers are operated electronically, although some of the older process control systems use air pressure in pneumatic devices. The operation of an electronic controller is performed by hardwired circuitry or computer software. The controller produces a small electrical signal that usually needs to be conditioned or modified before it is sent to the next element. For example, it must be amplified if it is applied to an electrical motor, or connected to a proportional air pressure if it is applied to a pneumatic positioner or a control valve. The control function is also performed by programmable logic controllers (PLCs) and panel-mounted microprocessor controllers.

Actuator. The **actuator** is the "muscle" of the system. It is a device that physically alters some type of energy or fuel supply, causing the controlled variable to match the desired set point. Examples of energy or fuel are the flow of steam, water, air, gas, or electrical current. A practical application is a commercial bakery where the objective is to keep the temperature in an oven at 375 degrees. The temperature is the controlled variable. The temperature is determined by how much gas is fed to the oven burner. A valve in the gas line controls the flow by the amount it opens or closes. The valve is the actuator in the system. In the reservoir system, the actuator is the flow control valve, connected to the inlet pipe. Other terms used are the *final control element,* or *final correcting device.* Common types of actuators are louvers, hydraulic cylinders, pumps, and motors.

Manipulated Variable. The amount of fuel or energy that is physically altered by the actuator is referred to as the **manipulated variable.** The amount at which the manipulated variable is changed by the actuator affects the condition of the controlled variable. In the commercial oven example, the gas is the manipulated variable, and the temperature is the controlled variable. In the reservoir system, the flow is the manipulated variable. The flow rate is altered by the control valve (actuator), which affects the condition of the controlled variable (level).

Manufacturing Process. The **manufacturing process** is the operation performed by the actuator to control a physical variable, such as the motion of a machine or the processing of a liquid.

Disturbance. A **disturbance** is a factor that upsets the manufacturing process being performed, causing a change in the controlled variable. In the reservoir system, the disturbances are the rainfall and evaporation that alter the water level.

A block diagram of an open-loop system is shown in Figure 1-6. The Controller, Actuator, and Manufacturing process blocks perform the same operations as the closed-loop system shown in Figure 1-5. However, instead of the error signal being applied to the controller, the set point provides its input. Also, there is no feedback loop, and a comparator is not used by the open-loop system.

It is possible for open-loop system to perform automated operations. For example, the washing machine that launders clothes in your home uses a timer to control the wash cycles. An industrial laundry machine also uses timing devices to perform the same functions but on a larger scale. However, there is no feedback loop that monitors and takes corrective action if the timer becomes inaccurate, the temperature of the water changes, or a major problem arises that requires the machine to shut down.

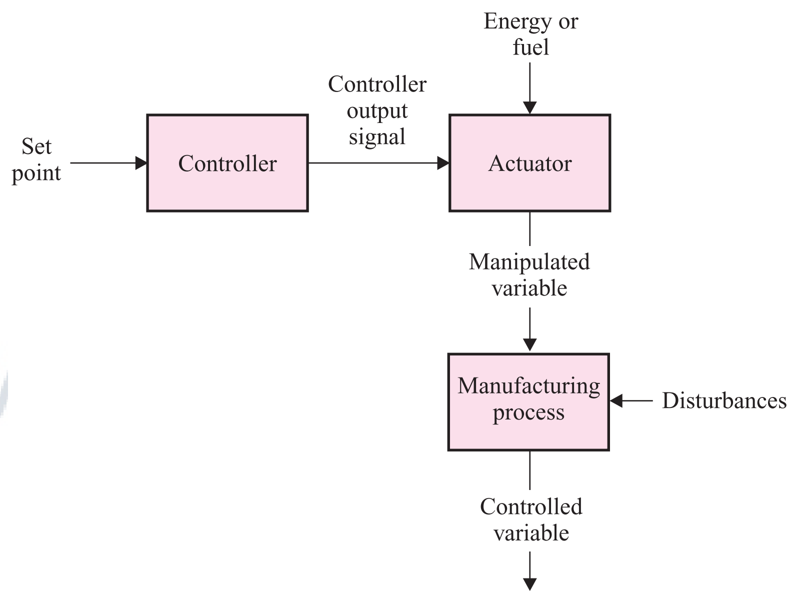


FIGURE 1-6 Open-loop block diagram that shows elements, input/output signals, and signal direction

1-3 Feedback Control

Industrial automated control is performed using closed-loop systems. The term “loop” is derived from the fact that, once the command signal is entered, it travels around the loop until equilibrium is restored.

To summarize the operation of a closed-loop system, the objective is to keep the controlled variable equal to the desired set point. A measurement device monitors the controlled variable and sends a measurement signal to the error detector that represents its condition along the feedback loop. An error detector compares the feedback signal to the set point and produces an error signal that is proportional to the difference between them. The error signal is fed to a controller, which determines which kind of action should occur to make the controlled variable equal to the set point. The output of the controller causes the actuator to physically adjust the manipulated variable. Altering the manipulated variable causes the condition of the controlled variable to change to the desired value.

The basic concept of feedback control is that an error must exist before some corrective action can be made. An error can develop in one of three ways:

1. The set point is changed.
2. A disturbance appears.
3. The load demand varies.

In the reservoir system, the set point is changed by adjusting the position of the float along linkage A. A disturbance is caused when rain supplies additional water to the tank, or evaporation lowers the level. The water flowing out of the tank to the irrigation system is referred to as the load. If the level of the water in the irrigation system suddenly lowers, the back pressure on the outlet pipe will decrease and cause the fluid to drain faster. This downstream condition is referred to as a load change. The set point and load demand are changes that normally occur in a system. The disturbance is an unwanted condition.

Feedback signals may be either positive or negative. If the feedback signal's polarity aids a command input signal, it is said to be positive or regenerative feedback. Positive feedback is used in radios. If the radio signal is weak, an Automatic Gain Control (AGC) circuit is activated. Its output is a feedback signal that boosts the radio signal's overall strength.

However, when positive feedback is used in industrial closed-loop systems, the input usually loses control over the output. If the feedback signal opposes the input signal, the system is said to use negative or degenerative feedback. By combining negative feedback values from the command signal, a closed-loop system works properly.

An example of closed-loop control that uses negative feedback is the central heating system in a house. The thermostat in Figure 1-7 monitors the temperature in the house and compares it to the desired reference setting. Suppose the room temperature drops to 66 degrees from the reference setting of 72 degrees. The measured feedback value is subtracted from the setpoint command and causes a six degree discrepancy. The thermostat contacts will close and cause the furnace to turn on. The furnace supplies heat until the temperature is back to the reference setting. When the negative feedback is sufficient to cancel the command, the error no longer exists. The thermostat then opens and switches the furnace off until the house cools down below the reference. As this cycle repeats, the temperature in the house is automatically maintained without human intervention.

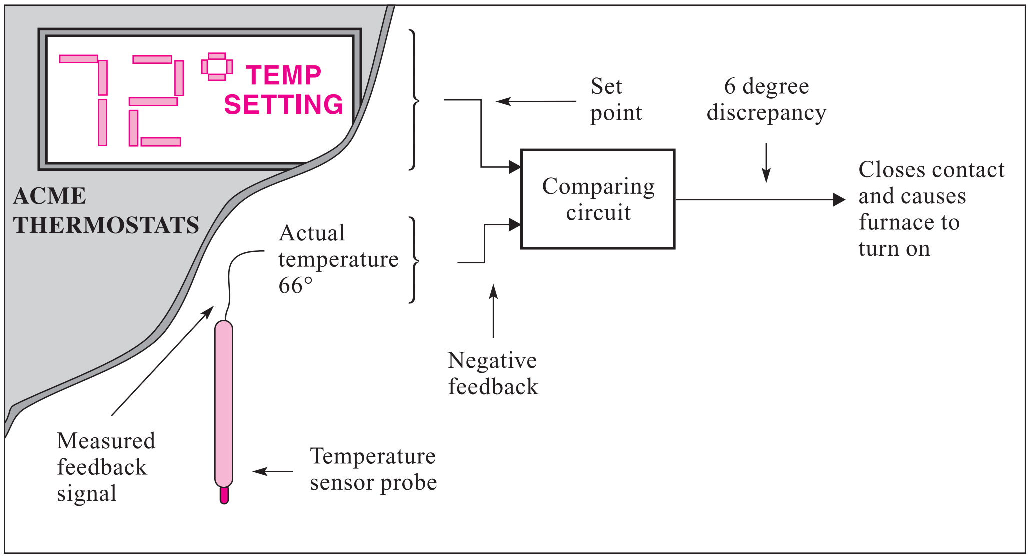


FIGURE 1-7 A thermostat uses a negative feedback signal to control the temperature of a house

The speed of an automobile can also be controlled automatically by a closed-loop system called a cruise control. The desired speed is set by an electronic mechanism usually placed on the steering wheel assembly. A Hall-effect speed sensor connected to the front axle generates a signal proportional to actual speed. An electronic error detector compares the actual speed to the desired speed, and then sends a signal representing the difference between them to a controller. The controller sends a demand signal to a vacuum device called an actuator. A part of the vacuum mechanism is a rod connected to the throttle, which varies the fuel flow to the engine. If a car that is traveling on a level road suddenly encounters an uphill grade, it begins to slow down. Because the actual speed is lower than the desired speed, the error detector sends a signal to the actuator. A vacuum is varied, which causes the rod to move the throttle so that more fuel flows to the engine. The additional fuel causes the car to accelerate until it reaches the desired speed.

1-4 Practical Feedback Application

An actual practical application of a feedback system used in a manufacturing process is shown in Figure 1-8. The diagram shows a heat exchanger. Its function is to supply water at a precise elevated temperature to a mixing vat that produces a chemical reaction. Cold water enters the bottom of the tank. The water is heated as it passes through steam-filled coils and leaves the tank through a port located at the top.

This example illustrates how the elements of a closed-loop feedback system provide automatic control. The elements consist of a thermal sensor, controller, and actuator. Together, they keep the temperature of the water that leaves the tank as close as possible to the set point when process conditions change.

There are three factors that can cause the condition of the controlled variable to become different from the set point. Two of the three factors are intentional. One intentional factor is changing the set point to a new desired temperature level. Another intentional factor is a *load change*. An example of a load change in the heat exchanger is an increase in the pump's flow rate so that the water leaves the top port of the tank much faster than usual. This condition would cause the water to flow through the tank more quickly. As a result, the water will not be heated as much as it flows through the coils causing the outgoing temperature to be lower.

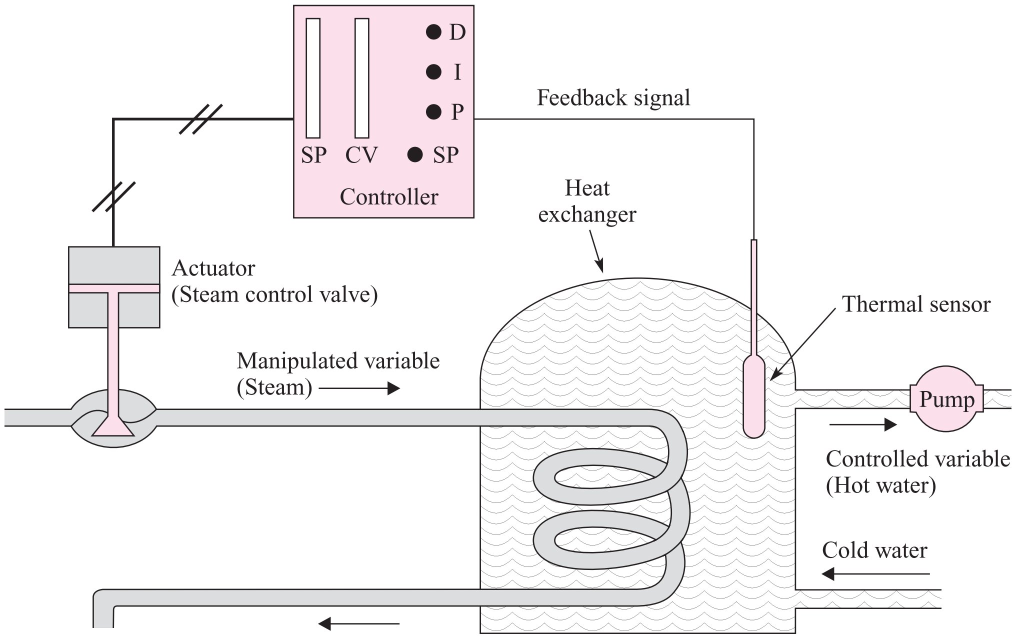


FIGURE 1-8 Closed-loop temperature control system

An unintentional factor is a *disturbance.* One example of a disturbance in the heat exchanger is a decrease in the temperature of the water entering the tank. When this condition exists, the temperature of the water in the tank will drop below set point. This situation occurs because the water entering the tank is colder. Since the temperature of the heating (steam) coils remains unchanged, the temperature of the water leaving the tank will be lower.

Whenever there is a difference between the set point and the condition of the controlled variable, the control system with feedback compensates for any error. For example, suppose that the temperature of the water leaving the heat exchanger falls below the set point. Thermal energy, which is the measured variable, is detected by the sensor. The sensor produces an electrical signal, which is the feedback signal to the controller. The controller compares the measured value to the set point. The size of the deviation determines the value of the controller output signal. This output signal goes to the final control element, which is a steam control valve. To return the water temperature back to the set point, the valve is opened farther by the actuator, allowing more steam, which is the manipulated variable, to enter the coils. As the coils become hotter, the temperature of the water, which passes through them, also rises.

As the water temperature returns to the set point, the deviation becomes smaller. The controller responds by changing its output signal to the valve. The new output signal causes the valve to reduce the flow of steam through the coils and causes the water to be heated at the proper rate.

1-5 Dynamic Response of a Closed-Loop System

The objective of a closed-loop system is to return the controlled variable back to the condition specified by the command signal when a set point change, a disturbance, or a load change occurs. However, there is not an immediate response. Instead, it takes a certain amount of time delay for the system to correct itself and re-establish a balanced condition. A measure of the loop's corrective action, as a function of time, is referred to as its **dynamic response.** There are several factors that contribute to the response delay:

- The response time of the instruments in the control loop. The instruments include the sensor, controller, and final control element. All instruments have a *time lag.* This is the time beginning when a change is received at its input ending at the time it produces an output.
- The **time duration** as a signal passes from one instrument in the loop to the next.
- The static inertia of the controlled variable. When energy is applied, the variable opposes being changed and creates a delay. Eventually the energy overcomes the resistance and causes the variable to reach its desired state. This delayed action is referred to as *pure lag.* The amount of lag is determined by the capacity (physical size) of the material; the lag is proportional to the amount of its mass. The type of material a controlled variable consists of also affects the lag. For example, the temperature of a gas will change more quickly than that of a liquid when exposed to thermal energy. The chemical properties of the controlled variable can also affect the amount of delay.
- The elapsed time between the instant a deviation of the controlled variable occurs and the corrective action begins. This factor is referred to as *dead time.* A pipeline which passes fluid can be used to illustrate an example of dead time. The control function of the closed-loop system is to regulate the temperature of the fluid flowing through the pipe. If the temperature of the fluid entering the pipe suddenly drops, there is a brief time period that passes before the fluid reaches a sensor downstream. The time from when the fluid enters the pipe until the sensor begins to initiate the closed-loop response is the dead time.

1-6 Feed-Forward Control

Two conditions can minimize the effectiveness of feedback control. The first is the occurrence of large magnitude disturbances. The second is long delays in the dynamic response of the control loop. To compensate for these limitations of feedback control, **feed-forward** control can be used.

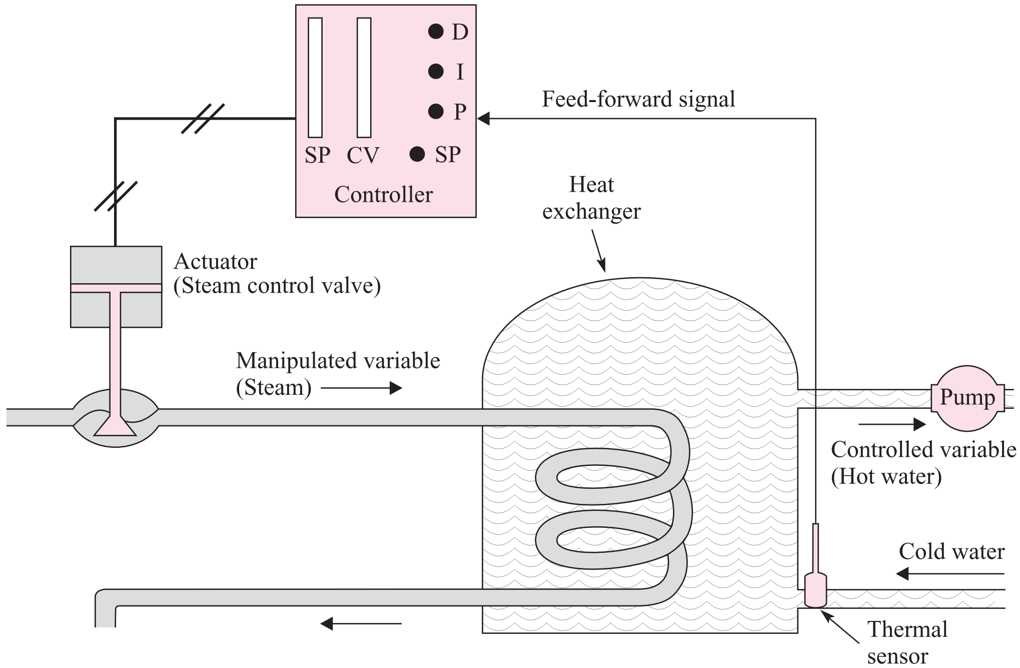


FIGURE 1-9 Feed-forward control of a temperature control system

The operation of feed-forward control is very different from feedback control. Feedback control takes corrective action after an error develops. The objective of feed-forward control is to prevent errors from occurring. Typically, feed-forward cannot prevent errors. Instead, it minimizes them.

The heat exchanger system described in Section 1-4 can be modified for feed-forward control, as shown in Figure 1-9. Instead of placing the thermal sensor inside the tank to detect a temperature deviation of the heated water, a thermal sensor is placed in the inlet pipe. As soon as there is a change in the temperature of the incoming cold water, it is detected before entering the tank. The controller responds by adjusting the position of the steam valve. By varying the steam through the coil at this time, corrective action occurs before the controlled variable leaving the outlet pipe can deviate from the setpoint temperature.

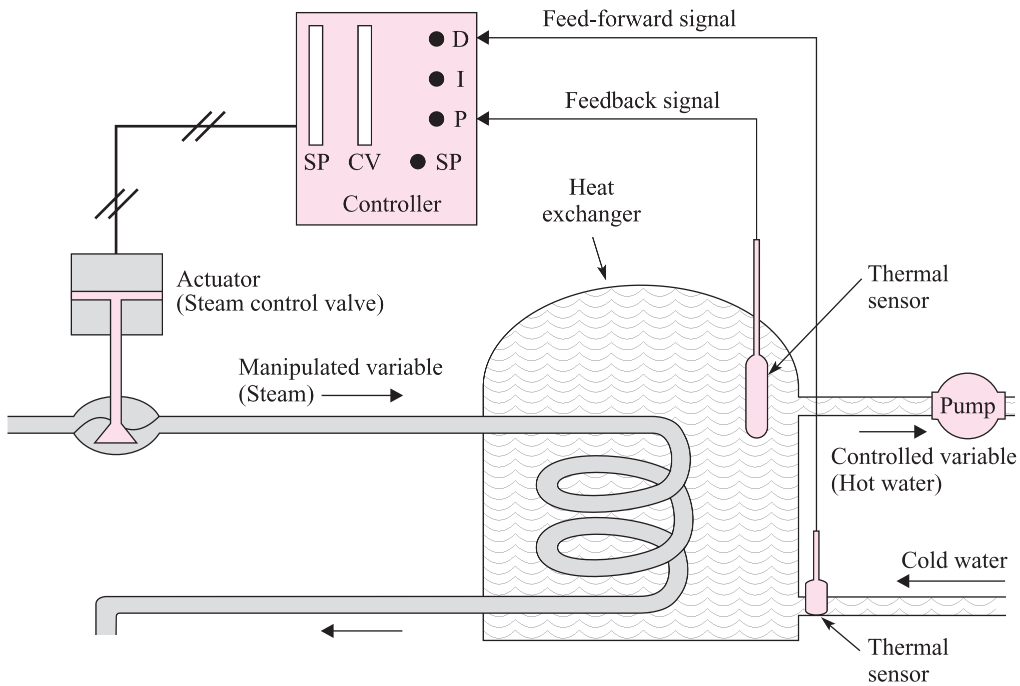


FIGURE 1-10 Feed-forward control loop with a feedback control loop

The feed-forward control system does not operate perfectly. There are always unmeasurable disturbances that cannot be detected, such as a worn flow valve, a sensor out of tolerance, or inexact mathematical calculations processed by the controller. Over a period of time, these unmeasurable disturbances affect the operation and eventually the water temperature in the tank, finally causing the water to reach an unacceptable temperature level. Due to the inaccuracy of feed-forward control, it is seldom used by itself. By adding feedback control to the system, corrections to the controller can be made if the controlled variable deviates from the set point due to unmeasurable disturbances.

Figure 1-10 shows a heat exchanger system that uses both feed-forward and feedback control. The controller receives input signals from two sensors. The sensor in the inlet line provides the feed-forward signal, and the sensor near the outlet provides the feedback signal.

In summary, feed-forward control adjusts the operation of the actuator to prevent changes in the controlled variable. Feed-forward controllers must make very sophisticated calculations to compute the changes of the actuator needed to compensate for variations in disturbances. Since they require highly skilled engineers, they typically are used only in critical applications within the plant.

Problems

1. The two classifications of industrial control systems are __________ control and __________ control.
2. List another name for each of the following terms.
   Motion Control
   Process Control
   Batch Process
3. A closed-loop industrial system typically uses __________ (negative, positive) feedback.
4. List two examples of controlled variables for motion control applications and two examples for process control applications.
   Motion Control
   Process Control
5. List one example of a measurement device for a motion control application and one example for a process control application.
   Motion Control
   Process Control
6. The control method used in ____ control applications is to sustain a constant condition of the controlled variable.
   a. servo b. process
7. An open-loop system does not have a ____.
   a. controller c. feedback loop
   b. final control element d. none of the above
8. T/F The measured variable represents the condition of the controlled variable.
9. The output of the measurement device is called the __________ __________.
10. Define set point.
11. The difference between the set point and feedback signal is referred to as the __________ signal, and is produced by the __________ detector.
12. T/F The controller can be considered the brain of a closed-loop system.
13. Altering the __________ variable causes the condition of the __________ variable to change.
    a. controlled b. manipulated
14. The device that provides the muscle to perform work in the closed-loop system is referred to as the __________.
15. The ____ is sent to the final control element.
    a. measured variable c. error signal
    b. feedback signal d. control signal
16. Which of the following influences cause a controlled variable to change? ____
    a. A disturbance occurs. c. The set point is adjusted.
    b. A load demand varies. d. All of the above.
17. Which of the following factors contribute to the dynamic response of a single control loop? ____
    a. The instrument in a control loop
    b. The inertia of the controlled variable
    c. Dead time
    d. All of the above
18. T/F The manipulated variable and controlled variable are synonymous terms in a closed-loop system.
19. T/F The basic concept of feedback control is that an error must exist before some corrective action can be made.
20. A pressurized tank must maintain a gas at 325 psi. A pressure sensor is used to measure the condition of the controlled variable. As the gas cools, the pressure in the tank decreases. When it drops to 300 psi, a valve is opened, which allows steam to flow to a heat exchanger inside the tank. The additional steam heats the gas and causes pressure to rise.
    ____ What is the controlled variable in this process?
    ____ What is the manipulated variable in this process?
    ____ What is the set point?
    ____ What is the measured variable?
    a. gas pressure d. 300 psi
    b. steam flow e. pressure
    c. 325 psi f. heat
21. T/F Feed-forward control is seldom used except in combination with feedback control.

22. Which of the following conditions are compensated for by using feed-forward control? ____
    a. Excessive lag time
    b. Large disturbances
    c. An error signal
    d. Feedback signal
23. The objective of ____ control is to prevent the controlled variable from deviating from the set point.
    a. feedback
    b. feed-forward
24. When feedback and feed-forward control are performed together, the primary function of feed-forward is to make corrections for ____ disturbances, and feedback control to make corrections for ____ disturbances.
    a. measurable
    b. unmeasurable

Answers to Odd-Numbered Problems

CHAPTER 1

1. motion, process or open-loop, closed-loop

3. negative

5. *Motion Control* — Hall-effect speed sensor; *Process Control* — Float

7. c. feedback loop

9. feedback signal

11. error, error

13. b. manipulated;
a. controlled

15. d. control signal

17. d. All of the above.

19. True

21. True

23. b. feed-forward