The goal is to place the fly accurately and lightly on the distant surface of the stream [59]. Describe the fly-casting process and a model of this process.

E1.6 An autofocus camera will adjust the distance of the lens from the film by using a beam of infrared or ultrasound to determine the distance to the subject [42]. Sketch a block diagram of this control system, and briefly explain its operation.

E1.7 Because a sailboat cannot sail directly into the wind, and traveling straight downwind is usually slow, the shortest sailing distance is rarely a straight line. Thus sailboats tack upwind—the familiar zigzag course—and jibe downwind. A tactician's decision of when to tack and where to go can determine the outcome of a race.

Describe the process of tacking a sailboat as the wind shifts direction. Sketch a block diagram depicting this process.

E1.8 Modern automated highways are being implemented around the world. Consider two highway lanes merging into a single lane. Describe a feedback control system carried on the automobile trailing the lead automobile that ensures that the vehicles merge with a prescribed gap between the two vehicles.

E1.9 Describe the block diagram of the control system of a skateboard with a human rider.

E1.10 Describe the process of human biofeedback used to regulate factors such as pain or body temperature. Biofeedback is a technique whereby a human can, with some success, consciously regulate pulse, reaction to pain, and body temperature.

E1.11 Future advanced commercial aircraft will be E-enabled. This will allow the aircraft to take advantage of continuing improvements in computer power and network growth. Aircraft can continuously communicate their location, speed, and critical health parameters to ground controllers, and gather and transmit local meteorological data. Sketch a block diagram showing how the meteorological data from multiple aircraft can be transmitted to the ground, combined using ground-based powerful networked computers to create an accurate weather situational awareness, and then transmitted back to the aircraft for optimal routing.

E1.12 Unmanned aerial vehicles (UAVs) are being developed to operate in the air autonomously for long periods of time. By autonomous, we mean that there is no interaction with human ground controllers. Sketch a block diagram of an autonomous UAV that is tasked for crop monitoring using aerial photography. The UAV must photograph and transmit the entire land area by flying a pre-specified trajectory as accurately as possible.

E1.13 Consider the inverted pendulum shown in Figure E1.13. Sketch the block diagram of a feedback control system. Identify the process, sensor, actuator, and controller. The objective is keep the pendulum in the upright position, that is to keep $\theta = 0$, in the presence of disturbances.

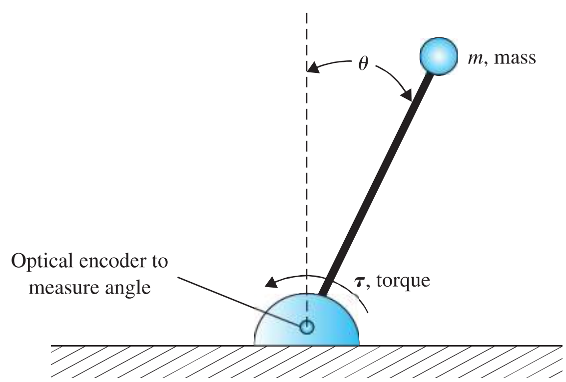

FIGURE E1.13 Inverted pendulum control.

E1.14 Sketch a block diagram of a person playing a video game. Suppose that the input device is a joystick and the game is being played on a desktop computer.

PROBLEMS

Problems require extending the concepts of this chapter to new situations.

The following systems may be described by a block diagram showing the cause–effect relationship and the feedback (if present). Each block should describe its function. Use Figure 1.3 as a model where appropriate.

P1.1 Many luxury automobiles have thermostatically controlled air-conditioning systems for the comfort of the passengers. Sketch a block diagram of an air-conditioning system where the driver sets the desired interior temperature. Identify the function of each element of the thermostatically controlled cooling system.

P1.2 Control systems can use a human operator as part of a closed-loop control system. Sketch the block diagram of the valve control system shown in Figure P1.2.

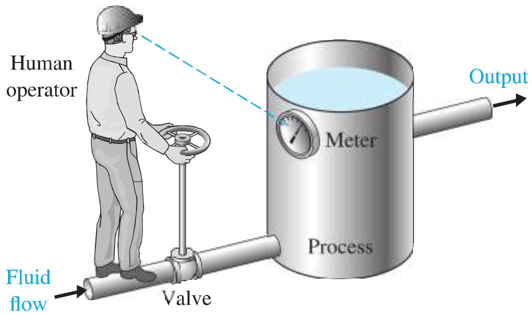

FIGURE P1.2 Fluid-flow control.

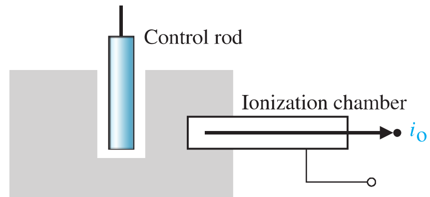

FIGURE P1.4 Nuclear reactor control.

P1.3 In a chemical process control system, it is valuable to control the chemical composition of the product. To do so, a measurement of the composition can be obtained by using an infrared stream analyzer, as shown in Figure P1.3. The valve on the additive stream may be controlled. Complete the control feedback loop, and sketch a block diagram describing the operation of the control loop.

P1.4 The accurate control of a nuclear reactor is important for power system generators. Assuming the number of neutrons present is proportional to the power level, an ionization chamber is used to measure the power level. The current i_o is proportional to the power level. The position of the graphite control rods moderates the power level. Complete the control system of the nuclear reactor shown in Figure P1.4 and sketch the block diagram describing the operation of the feedback control loop.

P1.5 A light-seeking control system, used to track the sun, is shown in Figure P1.5. The output shaft, driven by the motor through a worm reduction gear, has a bracket attached on which are mounted two photocells. Complete the closed-loop system so that the system follows the light source.

P1.6 Feedback systems do not always involve negative feedback. Economic inflation, which is evidenced by continually rising prices, is a **positive feedback** system. A positive feedback control system, as shown

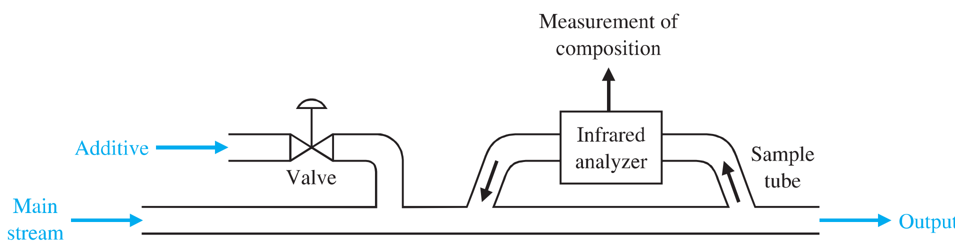

FIGURE P1.3 Chemical composition control.

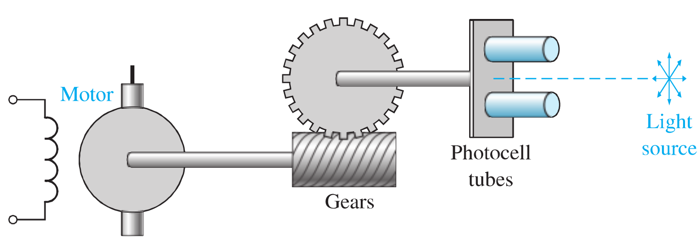

FIGURE P1.5 A photocell is mounted in each tube. The light reaching each cell is the same in both only when the light source is exactly in the middle as shown.

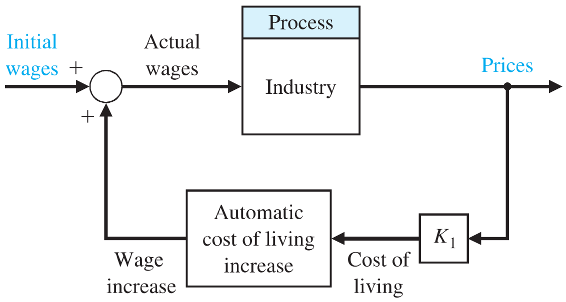

FIGURE P1.6 Positive feedback.

in Figure P1.6, adds the feedback signal to the input signal, and the resulting signal is used as the input to the process. A simple model of the price–wage inflationary spiral is shown in Figure P1.6. Add additional feedback loops, such as legislative control or control of the tax rate, to stabilize the system. It is assumed that an increase in workers' salaries, after some time delay, results in an increase in prices. Under what conditions could prices be stabilized by falsifying or delaying the availability of cost-of-living data? How would a national wage and price economic guideline program affect the feedback system?

P1.7 The story is told about the sergeant who stopped at the jewelry store every morning at nine o'clock and compared and reset his watch with the chronometer in the window. Finally, one day the sergeant went into the store and complimented the owner on the accuracy of the chronometer.

"Is it set according to time signals from Arlington?" asked the sergeant.

"No," said the owner, "I set it by the five o'clock cannon fired from the fort each afternoon. Tell me, Sergeant, why do you stop every day and check your watch?"

The sergeant replied, "I'm the gunner at the fort!"

Is the feedback prevalent in this case positive or negative? The jeweler's chronometer loses two minutes each 24-hour period and the sergeant's watch loses three minutes during each eight hours. What is the net time error of the cannon at the fort after 12 days?

P1.8 The student–teacher learning process is inherently a feedback process intended to reduce the system error to a minimum. Construct a feedback model of the learning process and identify each block of the system.

P1.9 Models of physiological control systems are valuable aids to the medical profession. A model of the heart-rate control system is shown in Figure P1.9 [23, 48]. This model includes the processing of the nerve signals by the brain. The heart-rate control system is, in fact, a multivariable system, and the variables x, y, w, v, z, and u are vector variables. In other words, the variable x represents many heart variables $x_1, x_2, \ldots, x_n$. Examine the model of the heart-rate control system and add or delete blocks, if necessary. Determine a control system model of one of the following physiological control systems:

1. Respiratory control system
2. Adrenaline control system
3. Human arm control system
4. Eye control system
5. Pancreas and the blood-sugar-level control system
6. Circulatory system

P1.10 The role of air traffic control systems is increasing as airplane traffic increases at busy airports. Engineers are developing air traffic control systems and collision avoidance systems using the Global Positioning System (GPS) navigation satellites [34, 55]. GPS allows each aircraft to know its position in the airspace landing corridor very precisely. Sketch a block diagram depicting how an air traffic controller might use GPS for aircraft collision avoidance.

P1.11 Automatic control of water level using a float level was used in the Middle East for a water clock [1, 11].

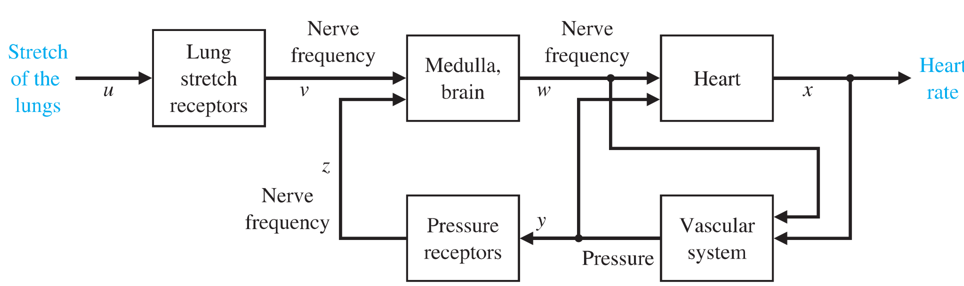

FIGURE P1.9 Heart-rate control.

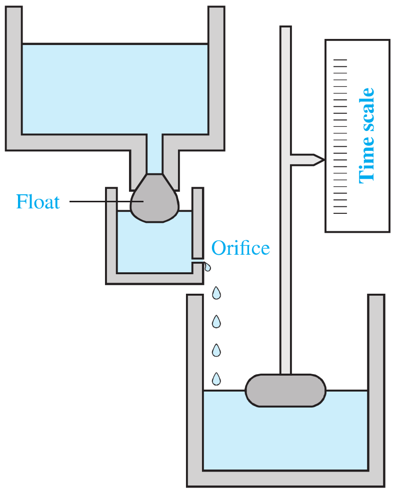

FIGURE P1.11 Water clock. (From Newton, Gould, and Kaiser, *Analytical Design of Linear Feedback Controls*. Wiley, New York, 1957, with permission.)

The water clock (Figure P1.11) was used from sometime before Christ until the 17th century. Discuss the operation of the water clock, and establish how the float provides a feedback control that maintains the accuracy of the clock. Sketch a block diagram of the feedback system.

P1.12 An automatic turning gear for windmills was invented by Meikle in about 1750 [1, 11]. The fantail gear shown in Figure P1.12 automatically turns the windmill into the wind. The fantail windmill at right angle to the mainsail is used to turn the turret.

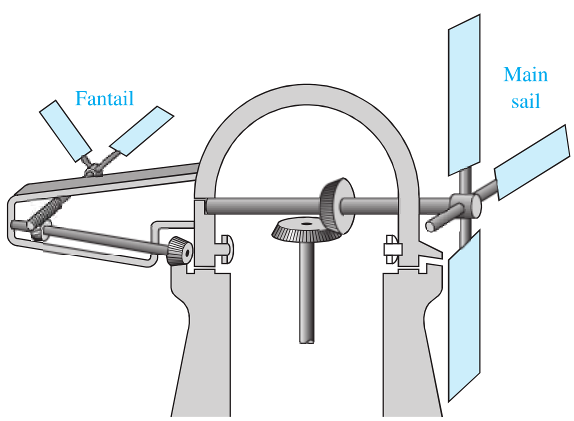

FIGURE P1.12 Automatic turning gear for windmills. (From Newton, Gould, and Kaiser, *Analytical Design of Linear Feedback Controls*. Wiley, New York, 1957, with permission.)

The gear ratio is of the order of 3000 to 1. Discuss the operation of the windmill, and establish the feedback operation that maintains the main sails into the wind.

P1.13 A common example of a two-input control system is a home shower with separate valves for hot and cold water. The objective is to obtain (1) a desired temperature of the shower water and (2) a desired flow of water. Sketch a block diagram of the closed-loop control system.

P1.14 Adam Smith (1723–1790) discussed the issue of free competition between the participants of an economy in his book *Wealth of Nations*. It may be said that Smith employed social feedback mechanisms to explain his theories [41]. Smith suggests that (1) the available workers as a whole compare the various possible employments and enter that one offering the greatest rewards, and (2) in any employment the rewards diminish as the number of competing workers rises. Let r = total of rewards averaged over all trades, c = total of rewards in a particular trade, and q = influx of workers into the specific trade. Sketch a feedback system to represent this system.

P1.15 Small computers are used in automobiles to control emissions and obtain improved gas mileage. A computer-controlled fuel injection system that automatically adjusts the fuel–air mixture ratio could improve gas mileage and reduce unwanted polluting emissions significantly. Sketch a block diagram for such a system for an automobile.

P1.16 All humans have experienced a fever associated with an illness. A fever is related to the changing of the control input in the body's thermostat. This thermostat, within the brain, normally regulates temperature near 98°F in spite of external temperatures ranging from 0°F to 100°F or more. For a fever, the input, or desired, temperature is increased. Even to many scientists, it often comes as a surprise to learn that fever does not indicate something wrong with body temperature control but rather well-contrived regulation at an elevated level of desired input. Sketch a block diagram of the temperature control system and explain how aspirin will lower a fever.

P1.17 Baseball players use feedback to judge a fly ball and to hit a pitch [35]. Describe a method used by a batter to judge the location of a pitch so that he can have the bat in the proper position to hit the ball.

P1.18 A cutaway view of a commonly used pressure regulator is shown in Figure P1.18. The desired pressure is set by turning a calibrated screw. This compresses the spring and sets up a force that opposes the upward motion of the diaphragm. The bottom side of the diaphragm is exposed to the water pressure that is to be controlled. Thus the motion of the diaphragm is an indication of the pressure difference between

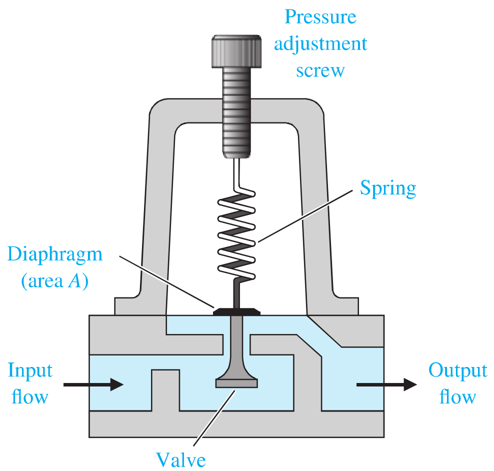

FIGURE P1.18 Pressure regulator.

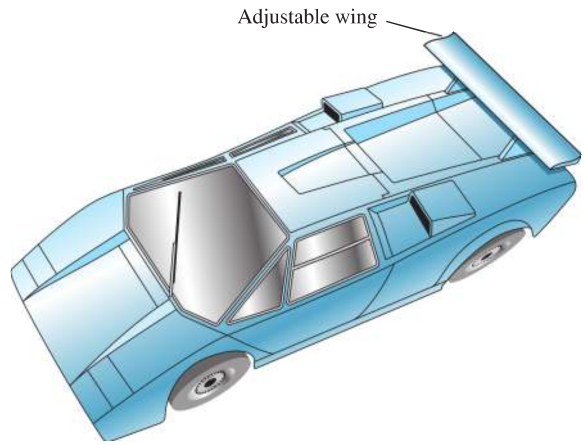

FIGURE P1.20 A high-performance race car with an adjustable wing.

the desired and the actual pressures. It acts like a comparator. The valve is connected to the diaphragm and moves according to the pressure difference until it reaches a position in which the difference is zero. Sketch a block diagram showing the control system with the output pressure as the regulated variable.

P1.19 Ichiro Masaki of General Motors has patented a system that automatically adjusts a car's speed to keep a safe distance from vehicles in front. Using a video camera, the system detects and stores a reference image of the car in front. It then compares this image with a stream of incoming live images as the two cars move down the highway and calculates the distance. Masaki suggests that the system could control steering as well as speed, allowing drivers to lock on to the car ahead and get a "computerized tow." Sketch a block diagram for the control system.

P1.20 A high-performance race car with an adjustable wing (airfoil) is shown in Figure P1.20. Develop a block diagram describing the ability of the airfoil to keep a constant road adhesion between the car's tires and the race track surface. Why is it important to maintain good road adhesion?

P1.21 The potential of employing two or more helicopters for transporting payloads that are too heavy for a single helicopter is a well-addressed issue in the civil and military rotorcraft design arenas [37]. Overall requirements can be satisfied more efficiently with a smaller aircraft by using multilift for infrequent peak demands. Hence the principal motivation for using multilift can be attributed to the promise of obtaining increased productivity without having to manufacture larger and more expensive helicopters. A specific case of a multilift arrangement where two helicopters jointly transport payloads has been named **twin lift**. Figure P1.21 shows a typical "two-point pendant" twin lift configuration in the lateral/vertical plane.

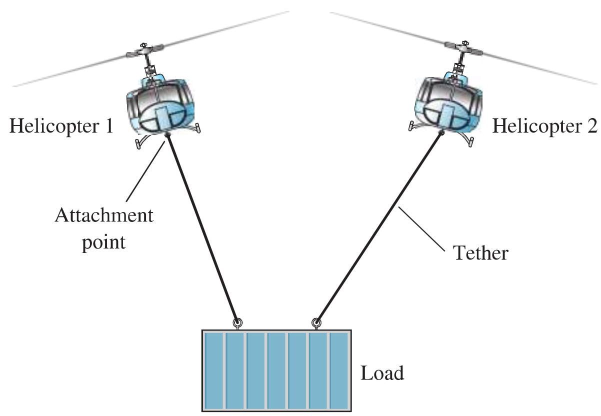

FIGURE P1.21 Two helicopters used to lift and move a large load.

Develop the block diagram describing the pilots' action, the position of each helicopter, and the position of the load.

P1.22 Engineers want to design a control system that will allow a building or other structure to react to the force of an earthquake much as a human would. The structure would yield to the force, but only so much, before developing strength to push back [47]. Develop a block diagram of a control system to reduce the effect of an earthquake force.

P1.23 Engineers at the Science University of Tokyo are developing a robot with a humanlike face [52]. The robot can display facial expressions, so that it can work cooperatively with human workers. Sketch a block diagram for a facial expression control system of your own design.

P1.24 An innovation for an intermittent automobile windshield wiper is the concept of adjusting its wiping cycle according to the intensity of the rain [54]. Sketch a block diagram of the wiper control system.

P1.25 In the past 50 years, over 20,000 metric tons of hardware have been placed in Earth's orbit. During the same time span, over 15,000 metric tons of hardware returned to Earth. The objects remaining in Earth's orbit range in size from large operational spacecraft to tiny flecks of paint. There are over 500,000 objects in Earth's orbit 1 cm or larger in size. About 20,000 of the space objects are currently tracked from groundstations on the Earth. Space traffic control [61] is becoming an important issue, especially for commercial satellite companies that plan to "fly" their satellites through orbit altitudes where other satellites are operating, and through areas where high concentrations of space debris may exist. Sketch a block diagram of a space traffic control system that commercial companies might use to keep their satellites safe from collisions while operating in space.

P1.26 NASA is developing a compact rover designed to transmit data from the surface of an asteroid back to Earth, as illustrated in Figure P1.26. The rover will use a camera to take panoramic shots of the asteroid surface. The rover can position itself so that the camera can be pointed straight down at the surface or straight up at the sky. Sketch a block diagram illustrating how the microrover can be positioned to point the camera in the desired direction. Assume that the pointing commands are relayed from the Earth to the microrover and that the position of the camera is measured and relayed back to Earth.

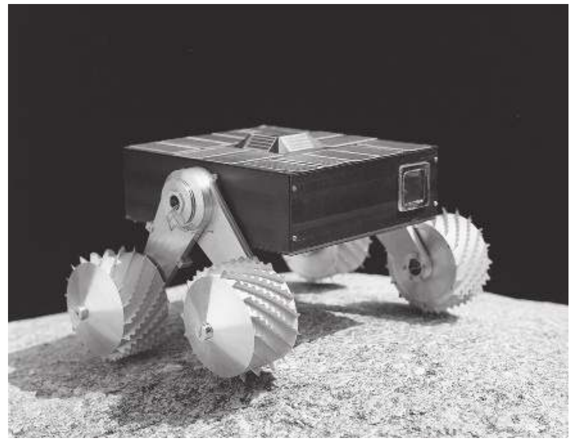

FIGURE P1.26 Microrover designed to explore an asteroid. (Photo courtesy of NASA.)

P1.27 A direct methanol fuel cell is an electrochemical device that converts a methanol water solution to electricity [75]. Like rechargeable batteries, fuel cells directly convert chemicals to energy; they are very often compared to batteries, specifically rechargeable batteries. However, one significant difference between rechargeable batteries and direct methanol fuel cells is that, by adding more methanol water solution, the fuel cells recharge instantly. Sketch a block diagram of the direct methanol fuel cell recharging system that uses feedback to continuously monitor and recharge the fuel cell.

ADVANCED PROBLEMS

Advanced problems represent problems of increasing complexity.

AP1.1 The development of robotic microsurgery devices will have major implications on delicate eye and brain surgical procedures. The microsurgery devices employ feedback control to reduce the effects of the surgeon's muscle tremors. Precision movements by an articulated robotic arm can greatly help a surgeon by providing a carefully controlled hand. One such device is shown in Figure AP1.1. The microsurgical devices have been evaluated in clinical procedures and are now being commercialized. Sketch a block diagram of the surgical process with a microsurgical device in the loop being operated by a surgeon. Assume that the position of the end-effector on the microsurgical device can be measured and is available for feedback.

AP1.2 Advanced wind energy systems are being installed in many locations throughout the world as a way for nations to deal with rising fuel prices and energy shortages, and to reduce the negative effects of fossil fuel utilization on the quality of the air. The modern windmill can be viewed as a mechatronic system. Think about how an advanced wind energy system would be designed as a mechatronic system. List the various components of the wind energy system and associate each component with one of the five elements

FIGURE AP1.1 Microsurgery robotic manipulator. (Photo courtesy of NASA.)

of a mechatronic system: physical system modeling, signals and systems, computers and logic systems, software and data acquisition, and sensors and actuators.

AP1.3 Many modern luxury automobiles have an autopark option. This feature will parallel park an automobile without driver intervention. Figure AP1.3 illustrates the parallel parking scenario. Sketch a block diagram of the automated parallel parking feedback control system. In your own words, describe the control problem and the challenges facing the designers of the control system.

AP1.4 Adaptive optics has applications to a wide variety of key control problems, including imaging of the human retina and large-scale, ground-based astronomical observations [98]. In both cases, the approach is to use a wavefront sensor to measure distortions in the incoming light and to actively control and compensate to the errors induced by the distortions. Consider the case of an extremely large ground-based optical telescope, possibly an optical telescope up to 100 meters in diameter. The telescope components include deformable mirrors actuated by micro-electro-mechanical (MEMS) devices and sensors to measure the distortion of the incoming light as it passes through the turbulent and uncertain atmosphere of Earth.

There is at least one major technological barrier to constructing a 100-m optical telescope. The numerical computations associated with the control and compensation of the extremely large optical telescope can be on the order of 10^{10} calculations each 1.5 ms. If we assume that the computational capability is available, then one can consider the design of a feedback control system that uses the available computational power. We can consider many control issues associated with the large-scale optical telescope. Some of the controls problems that might be considered include controlling the pointing of the main dish, controlling the individual deformable mirrors, and attenuating the deformation of the dish due to changes in outside temperature.

Describe a closed-loop feedback control system to control one of the deformable mirrors to compensate for the distortions in the incoming light. Figure AP1.4 shows a diagram of the telescope with a single deformable mirror. Suppose that the mirror has an associated MEMS actuator that can be used to vary the orientation. Also, assume that the wavefront

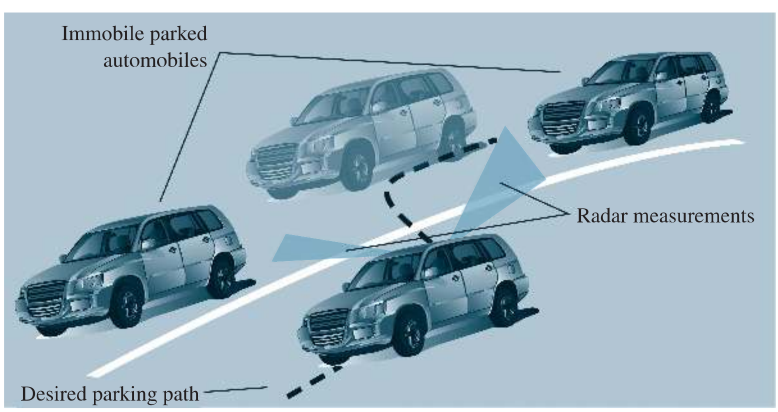

FIGURE AP1.3 Automated parallel parking of an automobile.

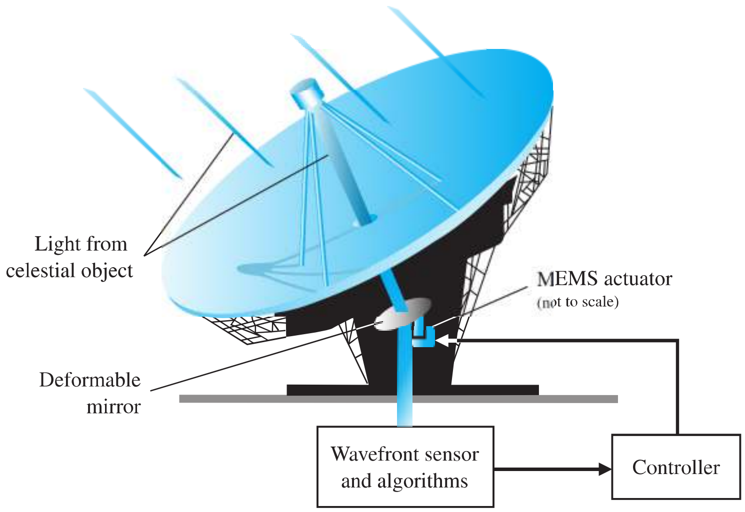

FIGURE AP1.4 Extremely large optical telescope with deformable mirrors for atmosphere compensation.

sensor and associated algorithms provide the desired configuration of the deformable mirror to the feedback control system.

AP1.5 The Burj Dubai is the tallest building in the world [94]. The building, shown in Figure AP1.5, stands at over 800 m with more than 160 stories. There are 57 elevators servicing this tallest free-standing structure in the world. Traveling at up to 10 m/s, the elevators have the world's longest travel distance from lowest to highest stop. Describe a closed-loop feedback control system that guides an elevator of a high-rise building to a desired floor while maintaining a reasonable transit time [95]. Remember that high accelerations will make the passengers uncomfortable.

AP1.6 Control systems are aiding humans in maintaining their homes. The robotic vacuum cleaner depicted in Figure AP1.6 is an example of a mechatronic system under active control that relies on infrared sensors and microchip technology to navigate around furniture. Describe a closed-loop feedback control system that guides the robotic vacuum cleaner to avoid collisions with obstacles [96].

FIGURE AP1.5 The world's tallest building in Dubai. (Photo courtesy of Obstando Images/Alamy.)

FIGURE AP1.6 A robotic vacuum cleaner communicates with the base station as it maneuvers around the room. (Photo courtesy of Hugh Threlfall/Alamy.)

DESIGN PROBLEMS

Design problems emphasize the design task. Continuous design problems (CDP) build upon a design problem from chapter to chapter.

CDP1.1 Increasingly stringent requirements of modern, high-precision machinery are placing increasing demands on slide systems [53]. The typical goal is to accurately control the desired path of the table shown in Figure CDP1.1. Sketch a block diagram model of a feedback system to achieve the desired goal. The table can move in the x direction as shown.

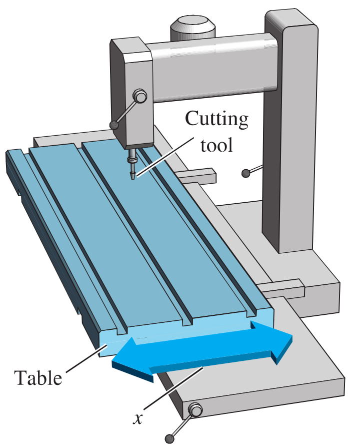

FIGURE CDP1.1 Machine tool with table.

DP1.1 The road and vehicle noise that invade an automobile's cabin hastens occupant fatigue [60]. Sketch a block diagram of an "antinoise" feedback system that will reduce the effect of unwanted noises. Indicate the device within each block.

DP1.2 Many cars are fitted with cruise control that, at the press of a button, automatically maintains a set speed. In this way, the driver can cruise at a speed limit or economic speed without continually checking the speedometer. Design a feedback-control in block diagram form for a cruise control system.

DP1.3 Describe a feedback control system in which a user utilizes a smart phone to remotely monitor and control a washing machine as illustrated in Figure DP1.3. The control system should be able to start and stop the wash cycle, control the amount of detergent and the water temperature, and provide notifications on the status of the cycle.

DP1.4 As part of the automation of a dairy farm, the automation of cow milking is under study [36]. Design a milking machine that can milk cows four or five times a day at the cow's demand. Sketch a block diagram and indicate the devices in each block.

FIGURE DP1.3 Using a smart phone to remotely monitor and control a washing machine. (Photo courtesy of Mikkel William/E+/Getty Images.)

DP1.5 A large, braced robot arm for welding large structures is shown in Figure DP1.5. Sketch the block diagram of a closed-loop feedback control system for accurately controlling the location of the weld tip.

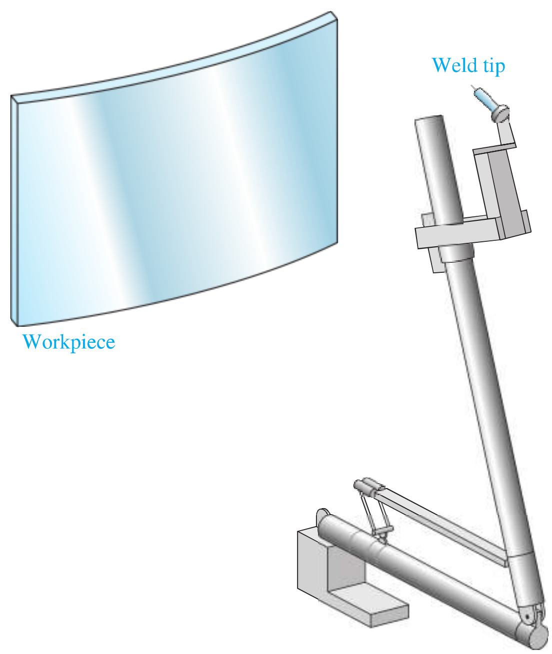

FIGURE DP1.5 Robot welder.

DP1.6 Vehicle traction control, which includes antiskid braking and antispin acceleration, can enhance vehicle performance and handling. The objective of this control is to maximize tire traction by preventing locked brakes as well as tire spinning during acceleration. Wheel slip, the difference between the vehicle speed and the wheel speed, is chosen as the controlled variable because of its strong influence on the tractive force between the tire and the road [19]. The adhesion coefficient between the wheel and the road reaches a maximum at a low slip. Develop a block diagram model of one wheel of a traction control system.

DP1.7 The Hubble space telescope was repaired and modified in space on several occasions [44, 46, 49]. One challenging problem with controlling the Hubble is damping the jitter that vibrates the spacecraft each time it passes into or out of the Earth's shadow. The worst vibration has a period of about 20 seconds, or a frequency of 0.05 hertz. Design a feedback system that will reduce the vibrations of the Hubble space telescope.

DP1.8 A challenging application of control design is the use of nanorobots in medicine. Nanorobots will require onboard computing capability, and very tiny sensors and actuators. Fortunately, advances in biomolecular computing, bio-sensors, and actuators are promising to enable medical nanorobots to emerge within the next decade [99]. Many interesting medical applications will benefit from nanorobotics. For example, one use might be to use the robotic devices to precisely deliver anti-HIV drugs or to combat cancer by targeted delivering of chemotherapy as illustrated in Figure DP1.8.

At the present time, we cannot construct practical nanorobots, but we can consider the control design process that would enable the eventual development and installation of these tiny devices in the medical field. Consider the problem of designing a nanorobot to deliver a cancer drug to a specific location within the human body. The target site might be the location of a tumor, for example. Suggest one or more control goals that might guide the design process. Recommend the variables that should be controlled and provide a list of reasonable specifications for those variables.

DP1.9 Consider the human transportation vehicle (HTV) depicted in Figure DP1.9. The self-balancing HTV is actively controlled to allow safe and easy transportation of a single person [97]. Describe a closed-loop feedback control system to assist the rider of the HTV in balancing and maneuvering the vehicle.

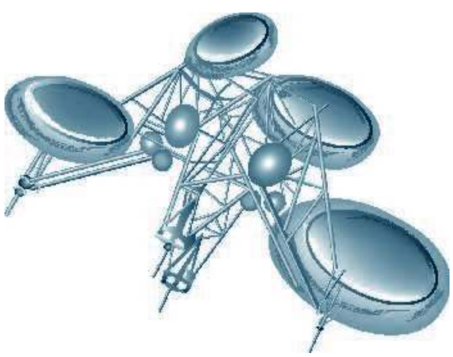

FIGURE DP1.8 An artist illustration of a nanorobot interacting with human blood cells.

FIGURE DP1.9 Personal transportation vehicle. (Photo courtesy of Sergiy Kuzmin/Shutterstock.)

ANSWERS TO SKILLS CHECK

True or False: (1) True; (2) True; (3) False; (4) False; (5) True

Multiple Choice: (6) d; (7) d; (8) b; (9) c; (10) a; (11) d; (12) a; (13) c; (14) d; (15) d

Word Match (in order, top to bottom): p, f, h, k, m, q, d, l, n, c, r, s, j, b, e, t, o, u, v, a, i, g