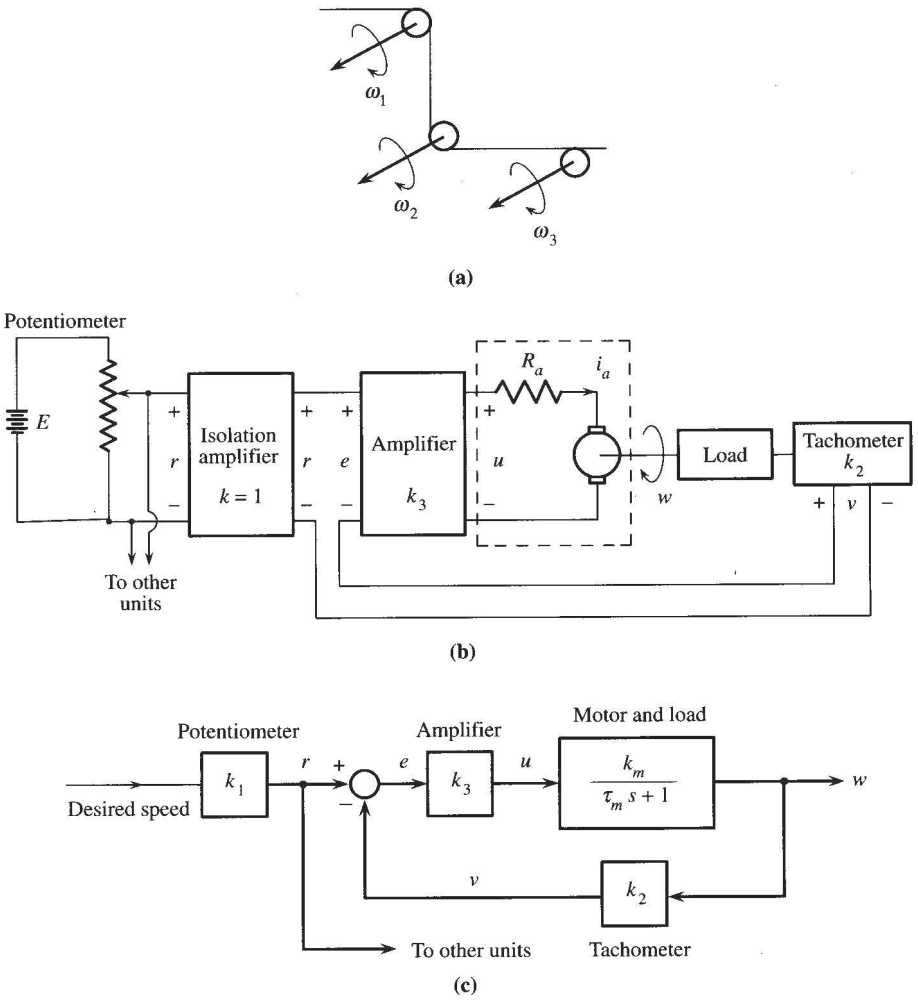


Figure 3.18 Speed control system.

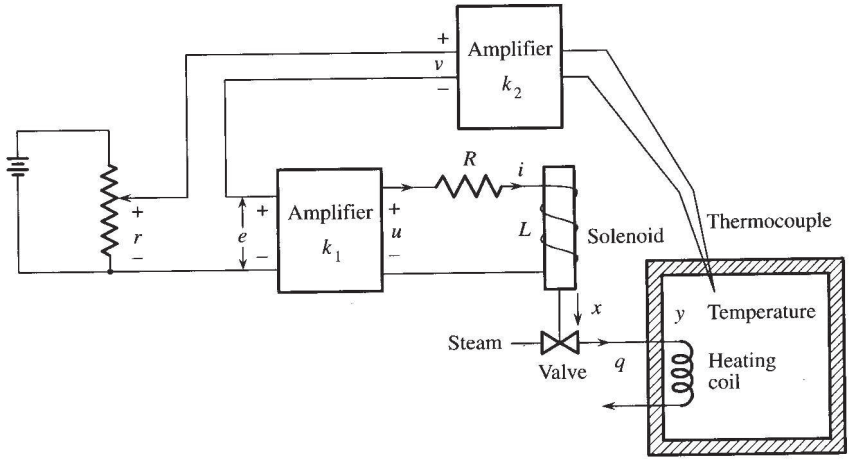
roller speed is transformed by a potentiometer into an electrical voltage. The loading problem associated with the potentiometer is eliminated by using an isolating amplifier. The scale on the potentiometer can be calibrated after the completion of the design. Therefore, there is no need to consider the potentiometer in the design. The roller speed is measured using a tachometer. The block diagram of the system is shown in Figure 3.18(c). For this problem, we are interested in the roller's speed, not its position, so the motor shaft speed is chosen as the output and the transfer function of the motor and load becomes $k_m/(\tau_m s + 1)$. Similarly, the tachometer's transfer function is k_2 rather than $k_2 s$ as shown. We mention that depending on the wiring, the error signal e can be $r - v$, $r + v$, or $v - r$. For the polarities shown in Figure 3.18(b), we have $e = r - v$.

Example 3.6.3

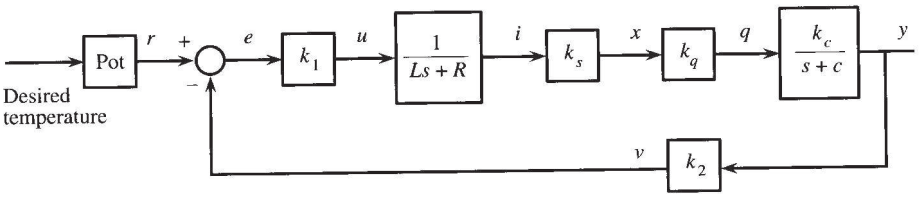
Temperature control is essential in many chemical processes. Consider the temperature control system shown in Figure 3.19(a). The problem is to control the temperature y inside the chamber. The chamber is heated by steam. The flow q of hot steam is proportional to the valve opening x; that is, $q = k_q x$. The valve opening x is controlled by a solenoid and is assumed to be proportional to the solenoid current i; that is, $x = k_s i$. It is assumed that the chamber temperature y and the steam flow q are related by

$$\frac{dy}{dt} = -cy + k_c q \tag{3.40}$$

where c depends on the insulation and the temperature difference between inside and outside the chamber. To simplify analysis and design, c is assumed to be a positive constant. This means that if no steam is pumped into the chamber, the temperature will decrease at the rate of e^{-ct}. The application of the Laplace transform



(a)



(b)

Figure 3.19 Temperature control system.

to (3.40) yields, assuming zero initial condition,

$$sY(s) = -cY(s) + k_c Q(s)$$

or

$$\frac{Y(s)}{Q(s)} = \frac{k_c}{s + c}$$

Thus the transfer function from q to y is $k_c/(s + c)$.

Figure 3.19(b) shows a block diagram for the heating system. The desired temperature is transformed into an electrical voltage r by the leftmost potentiometer. The scale on the potentiometer can be calibrated after the completion of the design. The chamber temperature is measured using a thermocouple and amplified to yield $v = k_2 y$. From the wiring, we have $e = r - v$ and the wiring is represented by the summer shown. The error signal e is amplified to yield u. The RL circuit is governed by

$$u(t) = Ri(t) + L\frac{di(t)}{dt}$$

The application of the Laplace transform yields, assuming zero initial condition,

$$U(s) = RI(s) + LsI(s)$$

which implies

$$\frac{I(s)}{U(s)} = \frac{1}{R + Ls} \tag{3.41}$$

Thus the transfer function from u to i is $1/(Ls + R)$ as shown. The remainder of the block diagram is self-explanatory.

Exercise 3.6.1

Develop the block diagrams in Figures 1.1, 1.6, and 1.7.

3.6.1 Reaction Wheels and Robotic Arms[5]

In this subsection, we give two more examples of developing block diagrams for control systems.

[5]May be skipped without loss of continuity.

Example 3.6.4

In order to point the antenna toward the earth or the solar panels toward the sun, the altitude or orientation of a satellite or space vehicle must be properly controlled. This can be achieved using gas jets or reaction wheels. Because of unlimited supply of electricity through solar panels, reaction wheels are used if the vehicle will travel for long journeys. Three sets of reaction wheels are needed to control the orientation in the three-dimensional space; but they are all identical.

A reaction wheel is actually a flywheel; it may be simply the rotor of a motor. It is assumed to be driven by an armature-controlled dc motor as shown in Figure 3.20(a) and (b). The case of the motor is rigidly attached to the vehicle. Because of the conservation of momentum, if the reaction wheel turns in one direction, the satellite will rotate in the opposite direction. The orientation and its rate of change can be measured using a gyro and a rate gyro. The block diagram of the control system is shown in Figure 3.20(c).

We derive in the following the transfer function $G(s)$ of the space vehicle and

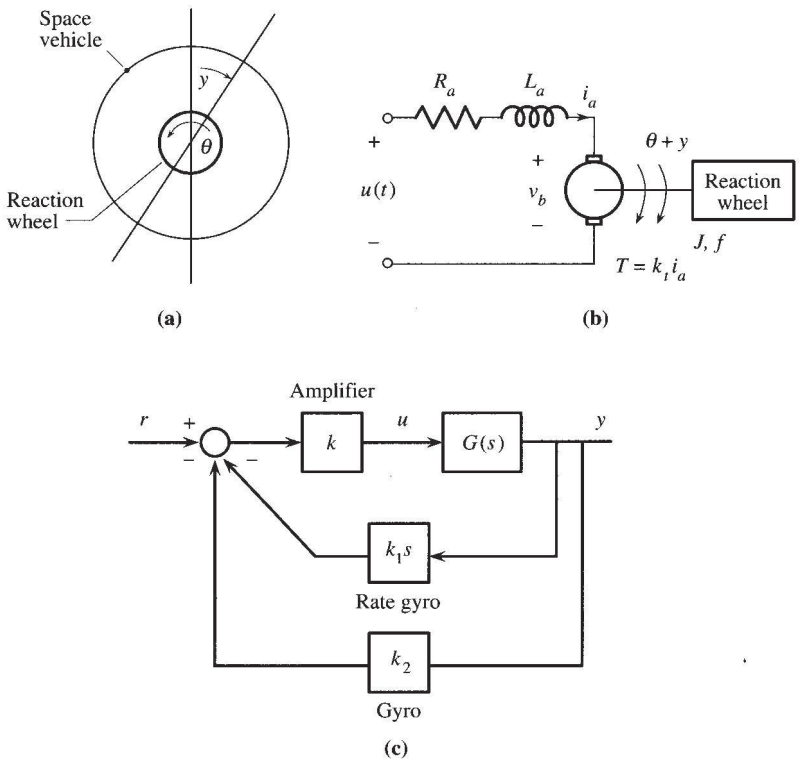


Figure 3.20 Altitude control of satellite.

motor. Let the angular displacements, with respect to the inertial coordinate, of the vehicle and the reaction wheel be respectively y and θ as shown in Figure 3.20(a). They are chosen, for convenience, to be in opposite directions. Clearly, the relative angular displacement of the reaction wheel (or the rotor of the motor) with respect to the vehicle (or the stator or case of the motor) is $y + \theta$. Thus the armature circuit is governed by, as in (3.10),

$$R_a i_a(t) + L_a \frac{di_a(t)}{dt} + v_b(t) = u(t) \tag{3.42}$$

with the back emf voltage $v_b(t)$ given by

$$v_b(t) = k_b \left(\frac{d\theta}{dt} + \frac{dy}{dt} \right) \tag{3.43}$$

Let J and f be the moment of inertia and the viscous friction coefficient on the motor shaft. Because the friction is generated between the motor shaft and the bearing that is attached to the satellite, the friction equals $f(d\theta/dt + dy/dt)$. Thus the torque equation is

$$T(t) = k_t i_a = J \frac{d^2\theta(t)}{dt^2} + f \left(\frac{d\theta}{dt} + \frac{dy}{dt} \right) \tag{3.44}$$

Let the moment of inertia of the vehicle be J_v. Then the conservation of angular momentum implies

$$J_v \frac{dy}{dt} = J \frac{d\theta}{dt} \tag{3.45}$$

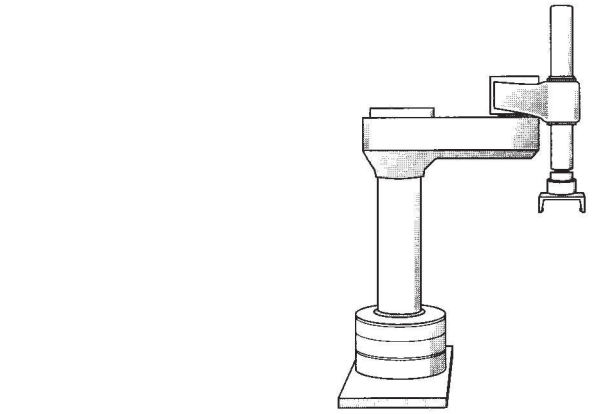
Using (3.42) through (3.45), we can show that the transfer function from u to y equals

$$G(s) = \frac{Y(s)}{U(s)} = \frac{k_t J}{s[(L_a s + R_a)(JJ_v s + (J + J_v)f) + k_t k_b (J + J_v)]} \tag{3.46}$$

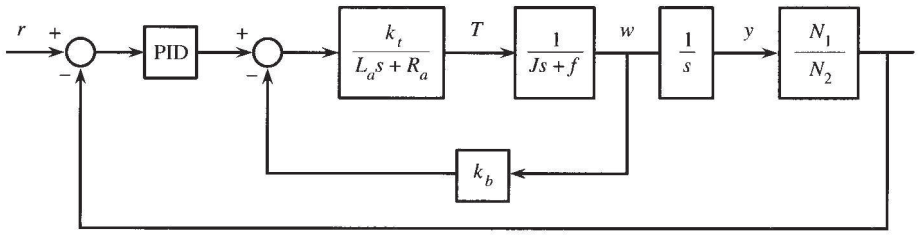
This completes the block diagram in Figure 3.20.

Example 3.6.5

Consider the industrial robot shown in Figure 3.21(a). The robot has a number of joints. It is assumed that each joint is driven by an armature-controlled dc motor through gears with gear ratio $n = N_1/N_2$. Figure 3.21(b) shows a block diagram of the control of a joint, where the block diagram in Figure 3.3 is used for the motor. The J and f in the diagram are the total moment of inertia and viscous friction coefficient reflected to the motor shaft by using (3.27). The compensator is a



(a)



(b)

Figure 3.21 (a) Industrial robot. (b) Joint control system.

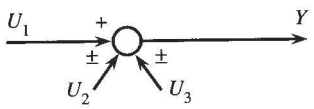
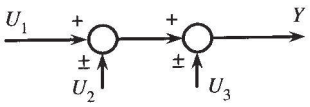
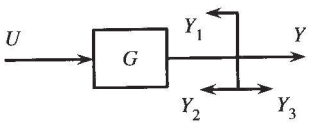
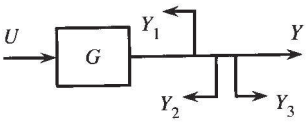
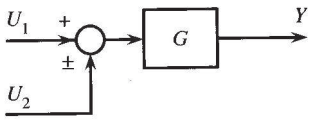
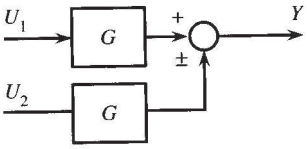
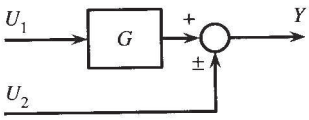
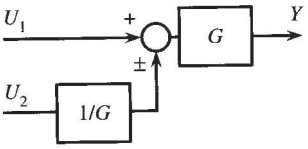
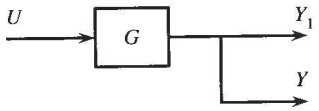
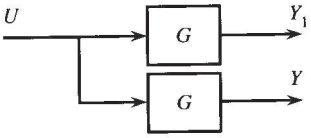
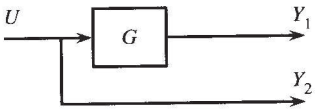
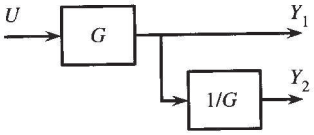
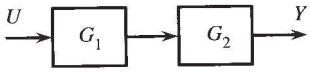
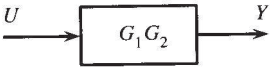
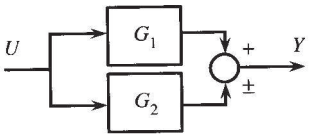
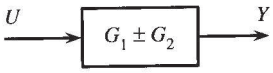
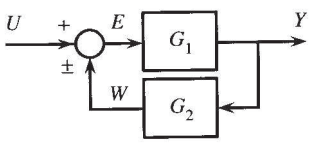
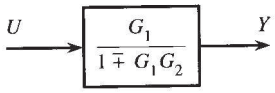
proportional-integral-derivative (PID) compensator, which will be discussed in later chapters.

3.7 MANIPULATION OF BLOCK DIAGRAMS

Once a block diagram for a control system is obtained, the next step in analysis is to simplify the block diagram to a single block or, equivalently, to find the overall transfer function. It is useless to analyze an individual block, because the behavior of the control system is affected only indirectly by individual transfer function. The behavior is dictated completely by its overall transfer function.

Two methods are available to compute overall transfer functions: block diagram manipulation and employment of Mason's formula. We discuss first the former and than the latter. The block diagram manipulation is based on the equivalent diagrams shown in Table 3.1. The first pair is concerned with summers. A summer must have two or more inputs and one and only one output. If a summer has three or more

Table 3.1 Equivalent Block Diagrams

1.		
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		

inputs, it can be separated into two summers as shown. A terminal can be branched out, at branching points, into several signals as shown in the second pair of Table 3.1 with all signals equal to each other. A summer or a branching point can be moved around a block as shown from the third to the sixth pair of the table. Their equivalences can be easily verified. For example, for the fourth pair, we have $Y = GU_1 \pm U_2$ for the left-hand-side diagram and $Y = G(U_1 \pm U_2/G) = GU_1 \pm U_2$ for the right-hand-side diagram. They are indeed equivalent.

The last three pairs of Table 3.1 are called, respectively, the *tandem*, *parallel*, and *feedback connections* of two blocks. The reduction of the tandem and parallel connections to single blocks is very simple. We now reduce the feedback connection to a single block. Note that if W is fed into the summer with a positive sign (that is, $E = U + W$), it is called *positive feedback*. If W is fed into the summer with a negative sign (that is, $E = U - W$), it is called *negative feedback*. We derive only the negative feedback part. Let the input of G_1 be denoted by E and the output of G_2 by W as shown in the left-hand-side diagram of the last pair of Table 3.1. Then we have

$$W = G_2Y \qquad E = U - W = U - G_2Y \qquad Y = G_1E \tag{3.47}$$

The substitution of the second equation into the last yields

$$Y = G_1(U - G_2Y) = G_1U - G_1G_2Y \tag{3.48}$$

which can be written as

$$(1 + G_1G_2)Y = G_1U$$

Thus we have

$$\frac{Y}{U} = \frac{G_1}{1 + G_1G_2} \tag{3.49}$$

This is the transfer function from U to Y, for the negative feedback part, as shown in the right-hand-side diagram of the last pair of Table 3.1. In conclusion, the transfer function of the feedback connection is $G_1/(1 + G_1G_2)$ for negative feedback and $G_1/(1 - G_1G_2)$ for positive feedback. They are important formulas, and should be remembered.

Now we use an example to illustrate the use of Table 3.1 to compute overall transfer functions of block diagrams.

Example 3.7.1

Consider the block diagram shown in Figure 3.22(a). We first use entry 9 in Table 3.1 to simplify the inner positive feedback loop as shown in Figure 3.22(b). Note that the direct feedback in Figure 3.22(a) is the same as feedback with transfer function 1 shown in Figure 3.22(b). Using entries 7 and 9, we have

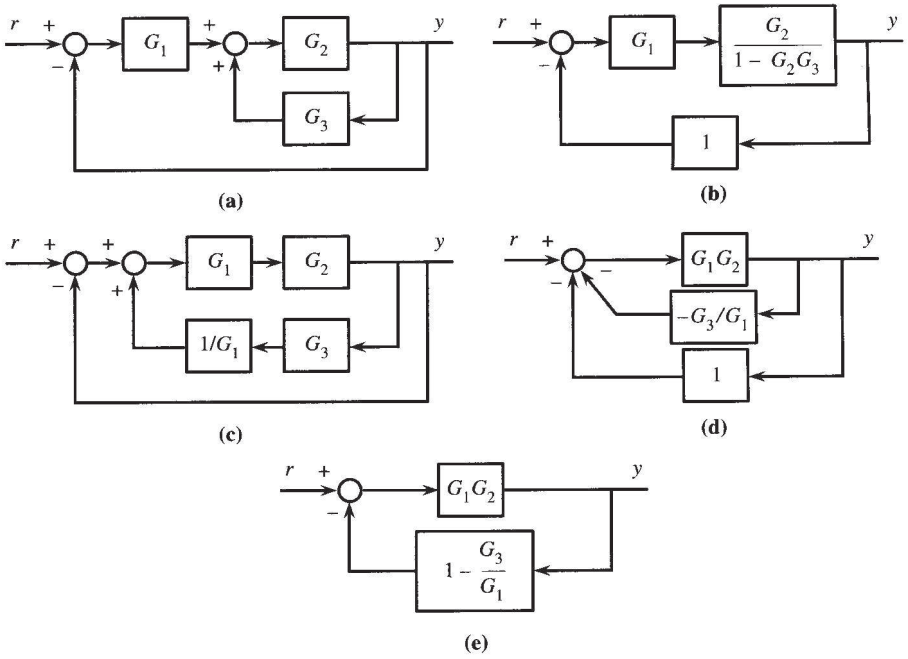


Figure 3.22 Manipulation of block diagram.

$$\frac{Y}{R} = \frac{G_1 \cdot \dfrac{G_2}{1 - G_2G_3}}{1 + G_1 \cdot \dfrac{G_2}{1 - G_2G_3} \cdot 1} = \frac{G_1G_2}{1 - G_2G_3 + G_1G_2} \tag{3.50}$$

This is the overall transfer function from R to Y in Figure 3.22(a).

A block diagram can be manipulated in many ways. For example, we can move the second summer in Figure 3.22(a) to the front of G_1, using entry 4 of Table 3.1, to yield the block diagram in Figure 3.22(c) which can be redrawn, using entry 1 of Table 3.1, as shown in Figure 3.22(d). Note that the positive feedback has been changed to a negative feedback, but we also have introduced a negative sign into the feedback block. The two feedback paths are in parallel and can be combined as shown in Figure 3.22(e). Thus we have

$$\frac{Y}{R} = \frac{G_1G_2}{1 + G_1G_2 \cdot \left(1 - \dfrac{G_3}{G_1}\right)} = \frac{G_1G_2}{1 + G_1G_2 - G_2G_3}$$

which is the same as (3.50), as expected.

Exercise 3.7.1

Use block manipulation to find the transfer functions from r to y of the block diagrams in Figure 3.23.

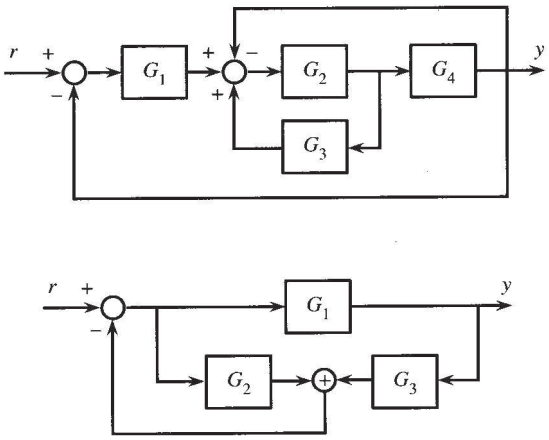


Figure 3.23 Block diagrams.

[**Answers:** $G_1G_2G_4/(1 - G_2G_3 + G_2G_4 + G_1G_2G_4)$, $G_1/(1 + G_2 + G_1G_3)$.]

3.7.1 Mason's Formula

Consider the block diagram shown in Figure 3.24. There are two inputs, r and p. The problem is to find the transfer function from r to y, denoted by G_{yr}, and the transfer function from p to y, denoted by G_{yp}. Because the system is linear, when we compute G_{yr}, we may assume $p = 0$ or, equivalently, disregard p. When we compute G_{yp}, we may disregard r. Once they are computed, the output y due to the

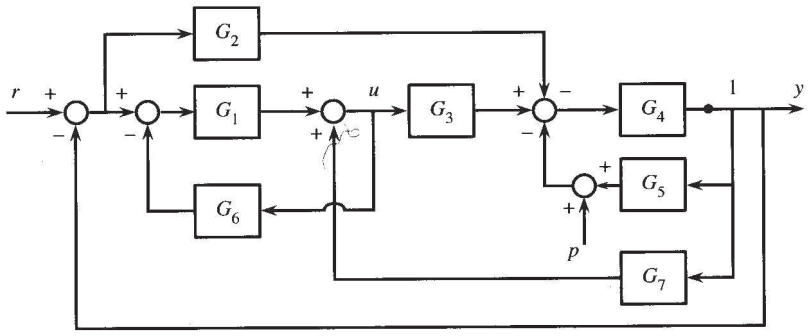


Figure 3.24 Block diagram.

two inputs r and p is given by

$$Y(s) = G_{yr}(s)R(s) + G_{yp}(s)P(s) \tag{3.51}$$

where Y, R, and P are respectively the Laplace transforms of y, r, and p.

Although G_{yr} and G_{yp} can be obtained by block manipulations, the manipulations are not simple. Furthermore, the manipulation in computing G_{yr} generally cannot be used to compute G_{yp}. Therefore, it requires two separate manipulations. In this subsection, we introduce a formula, called *Mason's formula*, to compute overall transfer functions that does not require any block manipulation.

The employment of Mason's formula requires the concepts of loops and forward paths. Consider the block diagram shown in Figure 3.24. Note that every block and branch is oriented, that is, unidirectional. A loop is any unidirectional path that originates and terminates at the same point and along which no point is encountered more than once. A *loop gain* is the product of all transfer functions along the loop. If a loop contains one or more summers, the sign at each summer must be considered in the loop gain. For example, the loop in Figure 3.25(a) has two summers. One branch enters the summer with a negative sign, one with a positive. The one with a negative sign can be changed to a positive sign by introducing a negative sign into G_2, as is shown in Figure 3.24(b). We remark that a branch with no block is the same as having a block with transfer function 1. Therefore the loop gain of the loop in Figure 3.25(a) or (b) is $G_1(-G_2) = -G_1G_2$. Similarly, the loop in Figure 3.25(c) has loop gain $-G_1(-G_2) = G_1G_2$. Now consider the block diagram in Figure 3.24. It has five loops with loop gains $-G_1G_6$, $-G_4G_5$, $G_3G_4G_7$, $-G_1G_3G_4$, and G_2G_4.

Two loops are said to be *nontouching* if they have no points in common. For example, the four loops in Figure 3.24 with loop gains $-G_4G_5$, $G_3G_4G_7$, $-G_1G_3G_4$, and G_2G_4 all touch each other because they all pass block G_4 or the point denoted by 1 in the diagram. The two loops with loop gains $-G_1G_6$ and $-G_4G_5$ do not touch each other; neither do the two loops with loop gains $-G_1G_6$ and G_2G_4. Now we define

$$\begin{aligned}\Delta = 1 &- (\Sigma \text{ loop gains}) \\ &+ (\Sigma \text{ products of all possible two nontouching loop gains}) \\ &- (\Sigma \text{ products of all possible three nontouching loop gains}) \\ &+ \cdots\end{aligned} \tag{3.52}$$

Although this formula looks very complicated, it is not necessarily so in its appli-

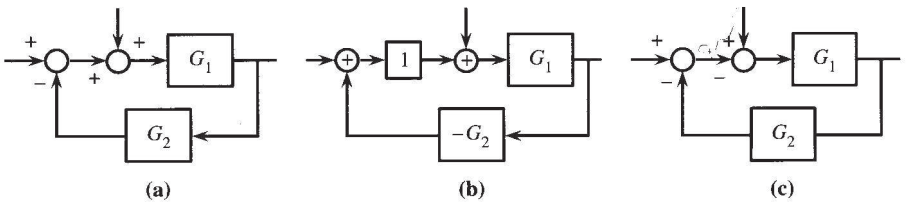


Figure 3.25 Block diagrams with a single loop.

cation. For example, if a block diagram has no loop as in the tandem and parallel connections in Table 3.1, then $\Delta = 1$. If a block diagram has only nontouching loops, then the formula terminates at the first parentheses. If a block diagram does not have three or more mutually nontouching loops, then the formula terminates at the second parentheses. For example, the block diagram in Figure 3.24 does not have three or more mutually nontouching loops, and we have

$$\begin{aligned}\Delta = 1 &- (-G_1G_6 - G_4G_5 + G_3G_4G_7 - G_1G_3G_4 + G_2G_4) \\ &+ ((-G_1G_6)(-G_4G_5) + (-G_1G_6)(G_2G_4))\end{aligned} \tag{3.53}$$

For easy reference, we call Δ the *characteristic function* of the block diagram. It is an inherent property of a block diagram and is independent of input and output terminals.

Now we introduce the concept of forward paths. It is defined for specific input/output pairs. A forward path from input r to output y is any connection of unidirectional branches and blocks from r to y along which no point is encountered more than once. A forward path gain is the product of all transfer functions along the path including signs at summers. For the block diagram in Figure 3.24, the r–y input/output pair has two forward paths, with gains $P_1 = G_1G_3G_4$ and $P_2 = -G_2G_4$. The p–y input/output pair has only one forward path, with gain $-G_4$. A loop touches a forward path if they have at least one point in common.

With these concepts, we are ready to introduce Mason's formula. The formula states that the overall transfer function from input v to output w of a block diagram is given by

$$G_{wv} = \frac{W(s)}{V(s)} = \frac{\Sigma_i P_i \Delta_i}{\Delta} \tag{3.54}$$

where Δ is defined as in (3.52),

P_i = the gain of the ith forward path from v to w

$\Delta_i = \Delta_{\text{set those loop gains to zero if they touch the } i\text{th forward path.}}$

and the summation is to be carried out for all forward paths from v to w. If there is no forward path from v to w, then $G_{wv} = 0$. Now we use the formula to compute G_{yr} and G_{py} for the block diagram in Figure 3.24. The Δ for the diagram was computed in (3.53). There are two forward paths from r to y, with $P_1 = G_1G_3G_4$ and $P_2 = -G_2G_4$. Because all loops touch the first forward path, we set all loop gains to zero in (3.53) to yield

$$\Delta_1 = 1$$

All loops except the one with loop gain $-G_1G_6$ touch the second forward path, therefore we have

$$\Delta_2 = 1 - (-G_1G_6) = 1 + G_1G_6$$

Thus we have

$$G_{yr} = \frac{Y(s)}{R(s)} = \frac{P_1\Delta_1 + P_2\Delta_2}{\Delta} \tag{3.55}$$

$$= \frac{G_1G_3G_4 \cdot 1 + (-G_2G_4)(1 + G_1G_6)}{1 + G_1G_6 + G_4G_5 - G_3G_4G_7 + G_1G_3G_4 - G_2G_4 + G_1G_6G_4G_5 - G_1G_6G_2G_4}$$

Now we find the transfer function from p to y in Figure 3.24. The Δ for the block diagram was computed in (3.53). There is only one forward path from p to y with gain $P_1 = -G_4$. Because all loops except the loop with loop gain $-G_1G_6$ touch the path, we have

$$\Delta_1 = 1 - (-G_1G_6) = 1 + G_1G_6$$

Thus the transfer function from p to y in Figure 3.24 is, using Mason's formula,

$$G_{yp} = \frac{Y(s)}{P(s)} = \frac{P_1\Delta_1}{\Delta} \tag{3.56}$$

$$= \frac{(-G_4)(1 + G_1G_6)}{1 + G_1G_6 + G_4G_5 - G_3G_4G_7 + G_1G_3G_4 - G_2G_4 + G_1G_6G_4G_5 - G_1G_6G_2G_4}$$

Exercise 3.7.2

Use Mason's formula to verify entries 7, 8, and 9 in Table 3.1.

Exercise 3.7.3

Find the transfer functions from r to u and from p to u in Figure 3.24.

[**Answers:** $G_{ur} = (G_1(1 + G_4G_5) - G_2G_4G_7)/\Delta$, $G_{up} = (-G_4G_7 + G_4G_1)/\Delta$, where Δ is given in (3.53).]

Exercise 3.7.4

Repeat Exercise 3.7.1 by using Mason's formula. Are the results the same?

3.7.2 Open-Loop and Closed-Loop Transfer Functions

Consider the block diagram shown in Figure 3.26(a). The transfer function from r to y, from p_1 to y, and from p_2 to y are respectively

$$G_{yr} = \frac{G_1G_2}{1 + G_1G_2} \qquad G_{yp_1} = \frac{G_2}{1 + G_1G_2} \qquad G_{yp_2} = \frac{1}{1 + G_1G_2} \tag{3.57}$$

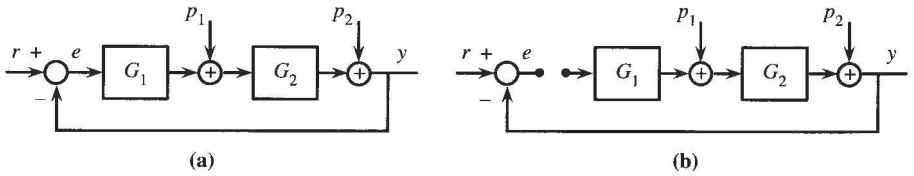


Figure 3.26 Closed-loop and open-loop systems.

These transfer functions are often referred to as *closed-loop transfer functions*. Now we open the loop at e as shown, and the resulting diagram becomes the one in Figure 3.26(b). The transfer functions from r to y, from p_1 to y, and from p_2 to y now become

$$G_{yr} = 0 \qquad G_{yp_1} = G_2 \qquad G_{yp_2} = 1$$

They are called *open-loop transfer functions*. We see that they are quite different from the closed-loop transfer functions in (3.57). This is not surprising, because the block diagrams in Figure 3.26 represent two distinctly different systems. Unless stated otherwise, all transfer functions in this text refer to closed-loop or overall transfer functions.

PROBLEMS

3.1. Consider a generator modeled as shown in Figure P3.1(a). The generator is driven by a diesel engine with a constant speed (not shown). The field circuit is assumed to have resistance R_f and inductance L_f; the generator has internal resistance R_g. The generated voltage $v_g(t)$ is assumed to be linearly proportional to the field current $i_f(t)$—that is, $v_g(t) = k_g i_f(t)$. Strictly speaking, $v_g(t)$ should appear at the generator terminals A and B. However, this would cause a loading problem in developing its block diagram. In order to eliminate this problem,

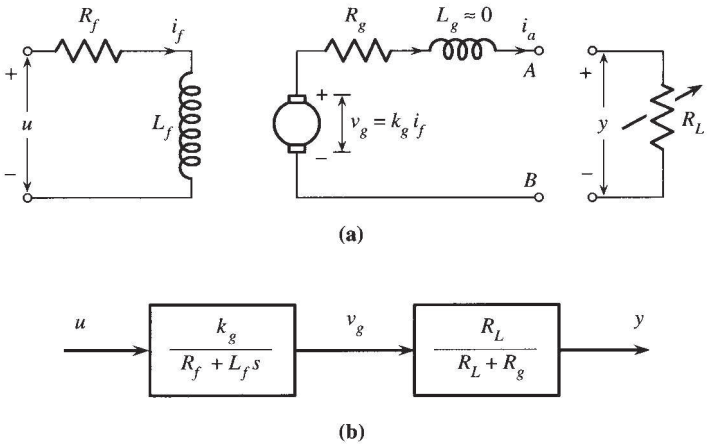


Figure P3.1

we assume that $v_g(t)$ appears as shown in Figure P3.1(a) and combine R_g with the load resistance R_L. Show that the generator can now be represented by the block diagram in Figure P3.1(b) and there is no loading problem in the block diagram. Where does the power of the generator come from? Does the flow of power appear in the block diagram?

3.2. Consider an armature-controlled dc motor driving a load as shown in Figure P3.2. Suppose the motor shaft is not rigid and must be modeled as a torsional spring with constant k_s. What is the transfer function from u to θ? What is the transfer function from u to $w = d\theta/dt$?

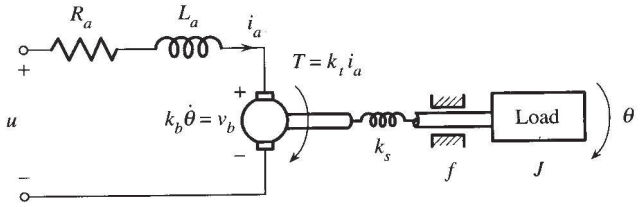


Figure P3.2

3.3. The combination of the generator and motor shown in Figure P3.3 is widely used in industry. It is called the *Ward-Leonard system.* Develop a block diagram for the system. Find the transfer functions from u to v_g and from v_g to θ.

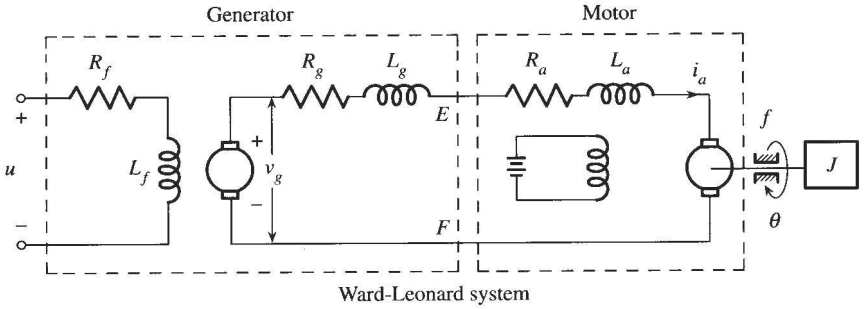


Figure P3.3

3.4. **a.** The system in Figure P3.4(a) can be used to control the voltage $v_o(t)$ of a generator that is connected to a load with resistance R_L. A reference signal $r(t)$, which can be adjusted by using a potentiometer, is applied through an amplifier with gain k_1 to the field circuit of the generator. Draw a block diagram for the system. The system is called an *open-loop voltage regulator.*

b. The system in Figure P3.4(b) can also be used to control the voltage $v_o(t)$. It differs from Figure P3.4(a) in that part of the output voltage or $v_1 = k_p v_o$ is subtracted from $r(t)$ to generate an error voltage $e(t)$. The error signal $e(t)$ is applied, through an amplifier with gain k_1, to the field circuit of the

generator. Develop a block diagram for the system. The system is called a *closed-loop* or *feedback voltage regulator.*

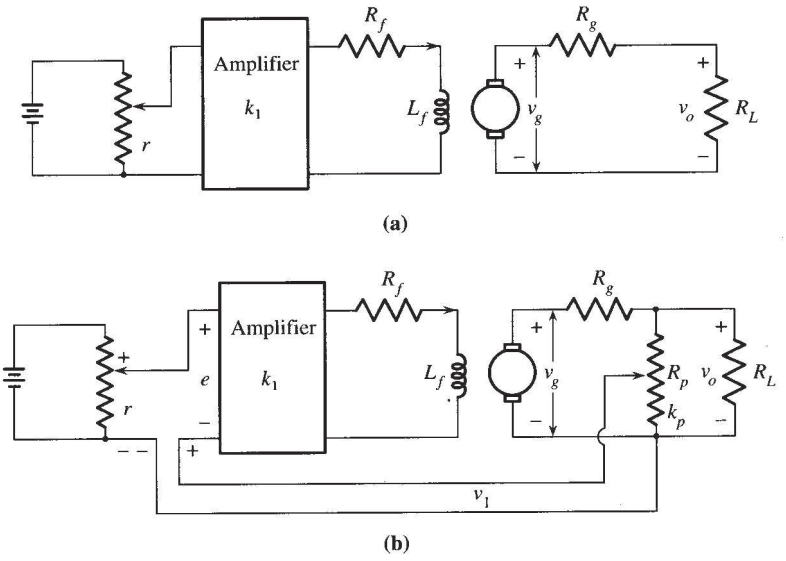


Figure P3.4

3.5. Consider the armature-controlled dc motor driving a load through a pair of gears shown in Figure 3.7(a). The following data are given:

$$R_a = 50\ \Omega \qquad k_t = 1\ \text{N·m·A}^{-1} \qquad k_b = 1\ \text{V·rad}^{-1}\text{·s},$$
$$N_1/N_2 = 1/2 \qquad J_2 = 12\ \text{N·m·rad}^{-1}\text{·s}^2 \qquad f_2 = 0.2\ \text{N·m·rad}^{-1}\text{·s},$$
$$J_1 = 0.1\ \text{N·m·rad}^{-1}\text{·s}^2, \qquad f_1 = 0.01\ \text{N·m·rad}^{-1}\text{·s}$$

Draw a block diagram for the system. Also compute their transfer functions.

3.6. Consider the gear train shown in Figure P3.6(a). Show that it is equivalent to the one in Figure P3.6(b) with

$$J_{1\text{eq}} = J_1 + J_2\left(\frac{N_1}{N_2}\right)^2 + J_3\left(\frac{N_1N_3}{N_2N_4}\right)^2$$
$$f_{1\text{eq}} = f_1 + f_2\left(\frac{N_1}{N_2}\right)^2 + f_3\left(\frac{N_1N_3}{N_2N_4}\right)^2$$

3.7. Find the transfer functions from v_i to v_o of the op-amp circuits shown in Figure P3.7.

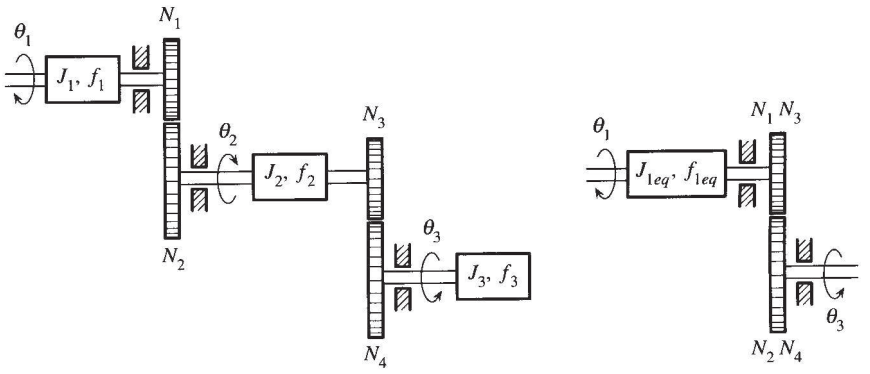


Figure P3.6

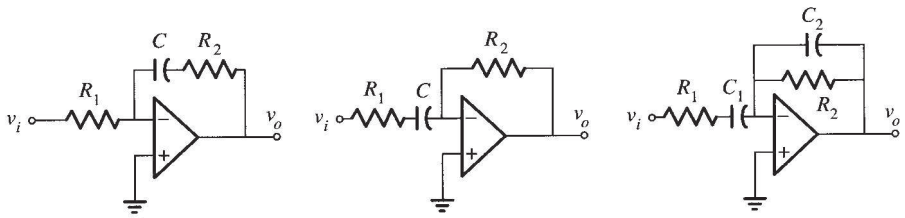


Figure P3.7

3.8. Consider the operational amplifier circuit shown in Figure P3.8. Show that the output v_o equals

$$v_o = \frac{R_f}{R}(v_B - v_A)$$

This is called a *differential* amplifier.

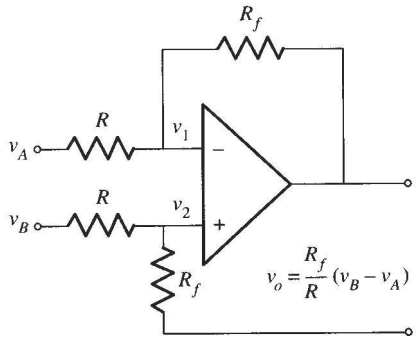


Figure P3.8

3.9. Develop a block diagram for the system shown in Figure P3.9. Compute also the transfer function of each block.

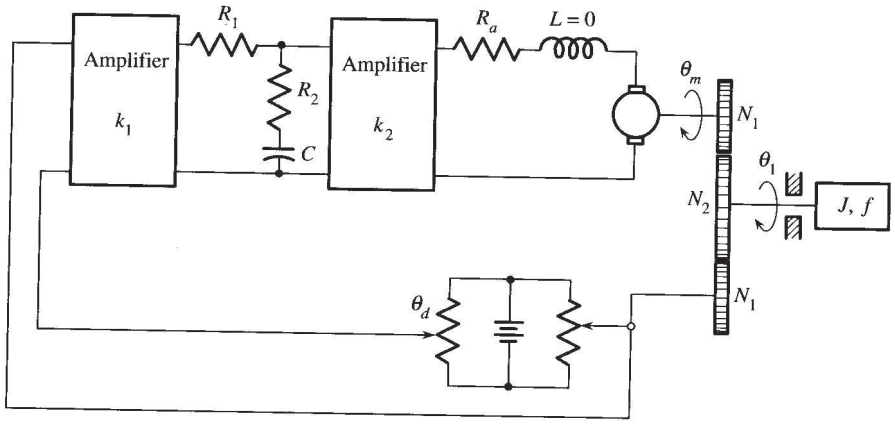


Figure P3.9

3.10. Consider the temperature control system shown in Figure P3.10. It is assumed that the heat q pumped into the chamber is proportional to u and the temperature y inside the chamber is related to q by the differential equation $dy(t)/dt = -0.3y(t) + 0.1q(t)$. Develop a block diagram for the system and compute the transfer function of each block.

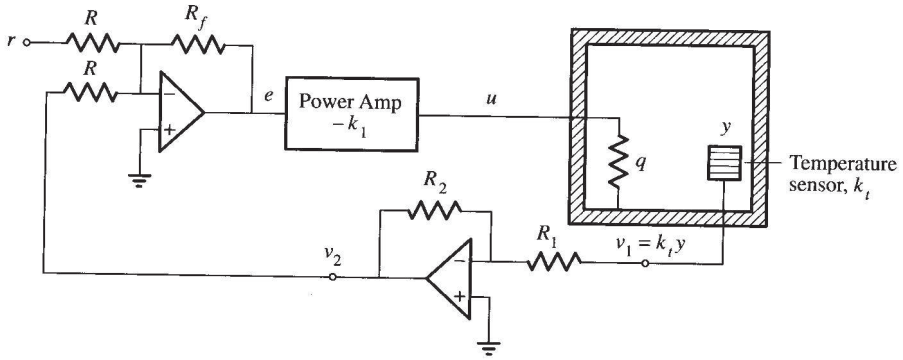


Figure P3.10

3.11. In addition to electromechanical transducers, optical transducers are also used in practice. The transducer shown in Figure P3.11 consists of a pulse generator and a pulse counter. By counting the number of pulses in a fixed interval of time, a signal proportional to the angular speed of the motor shaft can be generated. This signal is in digital form. Using a digital-to-analog converter and neglecting the so-called quantization error, the transfer function from θ to

v shown in Figure P3.10 can be approximated by ks. Draw a block diagram for the system. Indicate also the type of transfer function for each block.

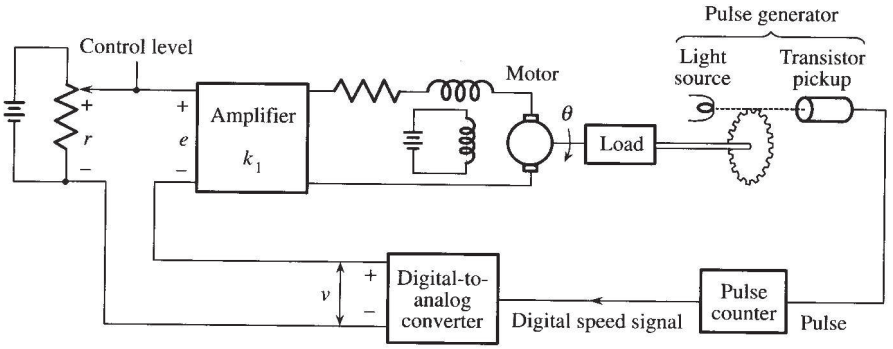


Figure P3.11

3.12. Machine tools can be controlled automatically by the instruction recorded on punched cards or tapes. This kind of control is called the *numerical control* of machine tools. Numerical control can be classified as position control and continuous contour control. A schematic diagram of a position control system is shown in Figure P3.12. A feedback loop is introduced in the D/A (digital-to-analog) converter to obtain a more accurate conversion. Draw a block diagram from θ_d to θ_o for the system. Indicate also the type of transfer function for each block.

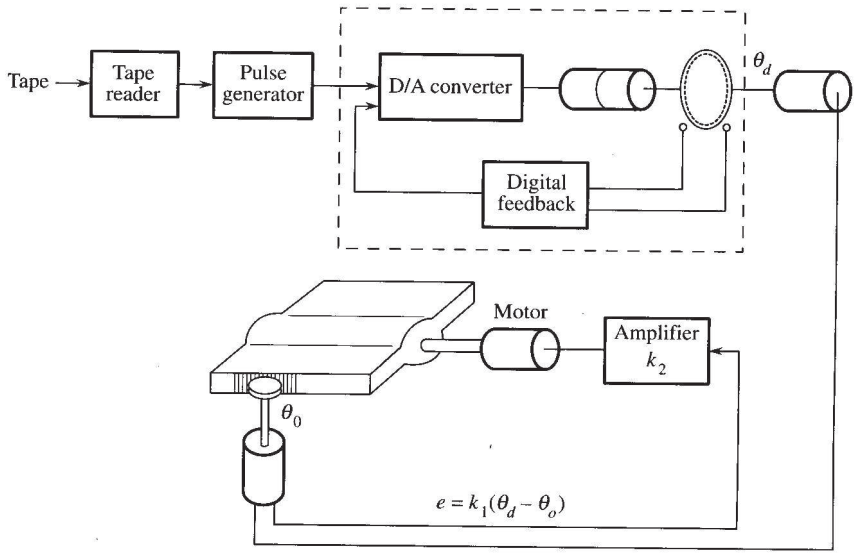
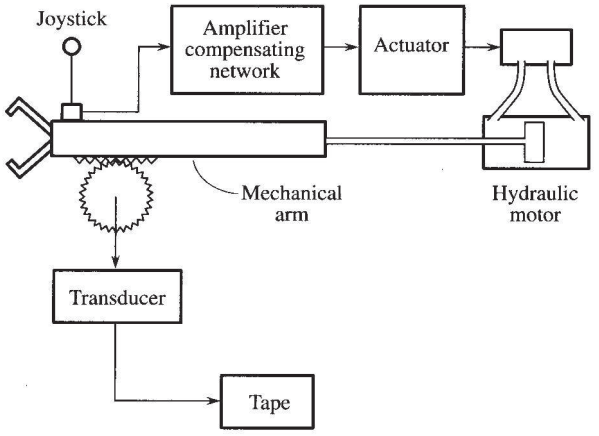
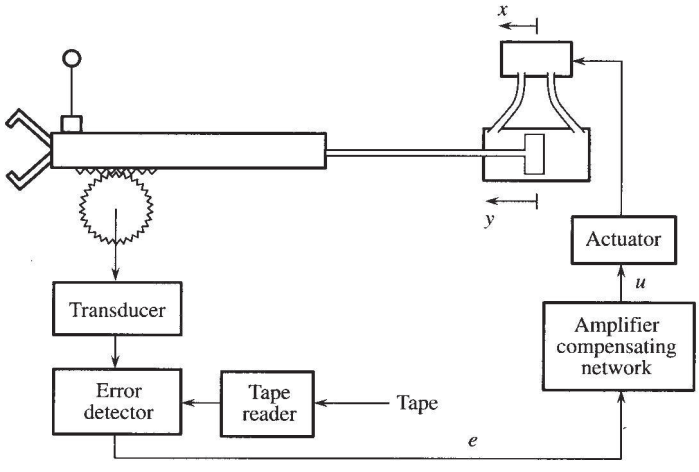


Figure P3.12

3.13. In industry, a robot can be designed to replace a human operator to carry out repeated movements. Schematic diagrams for such a robot are shown in Figure P3.13. The desired movement is first applied by an operator to the joystick shown. The joystick activates the hydraulic motor and the mechanical arm. The movement of the arm is recorded on a tape, as shown in Figure P3.13(a). The tape can then be used to control the mechanical arm, as shown in Figure P3.13(b). It is assumed that the signal x is proportional to u, and the transfer function from x to y is $k_m/s(\tau_m s + 1)$. Draw a block diagram for the system in Figure P3.13(b). Indicate also the type of transfer function for each block.



(a)



(b)

Figure P3.13

3.14. Use Table 3.1 to reduce the block diagrams shown in Figure P3.14 to single blocks.

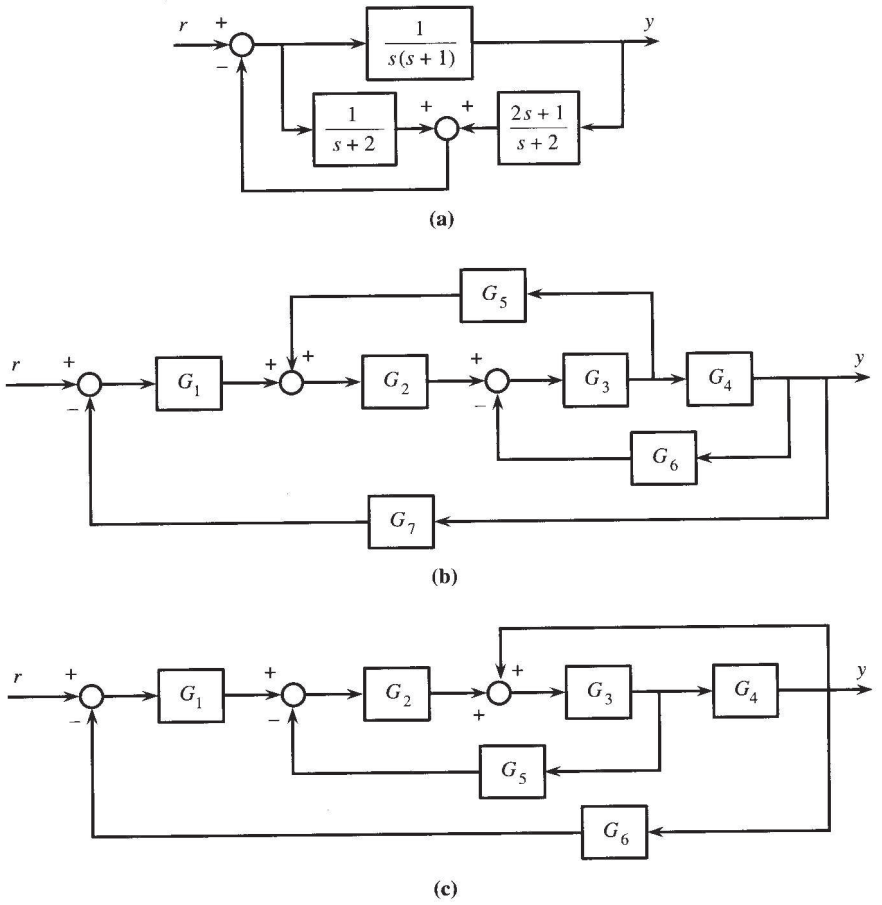


Figure P3.14

3.15. Use Mason's formula to repeat Problem 3.14.

3.16. Use Mason's formula to compute the transfer functions from r_1 to y and r_2 to y of the block diagram shown in Figure P3.16.

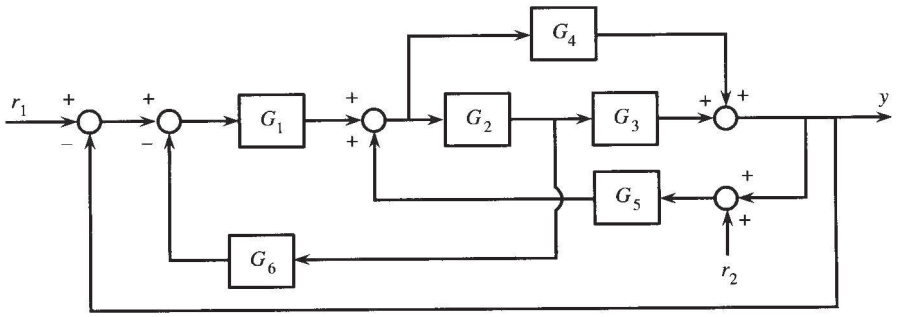


Figure P3.16

3.17. Consider the block diagram shown in Figure P3.17. It is the connection of the block diagram of an armature-controlled dc motor and that of a tachometer. Suppose noises may enter the system as shown. Compute the transfer functions from n_1 to w and from n_2 to w. Are they proper transfer functions?

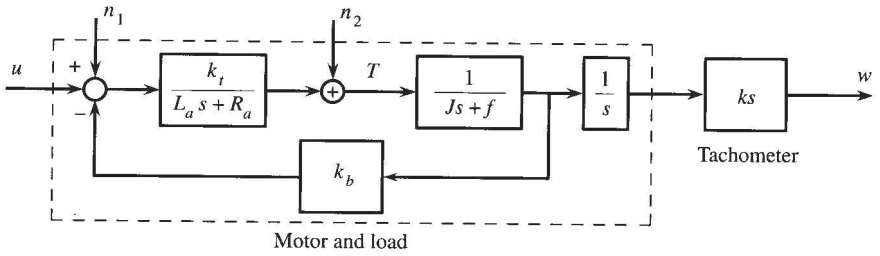


Figure P3.17