CHAPTER TWO

Control Systems Terminology

2.1 Block Diagrams: Fundamentals

A block diagram is a shorthand, pictorial representation of the cause-and-effect relationship between the input and output of a physical system. It provides a convenient and useful method for characterizing the ‘functional relationships among the various components of a control system. System components are alternatively called elements of the system. The simplest form of the block diagram is the single block, with one input and one output, as shown in Fig. 2-1.

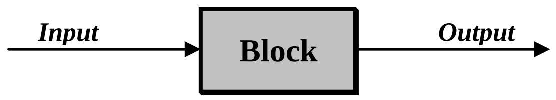

Fig. 2-1

The interior of the rectangle representing the block usually contains a description of or the name of the element, or the symbol for the mathematical operation to be performed on the input to yield the output. The arrows represent the direction of information or signal flow.

Example 2.1

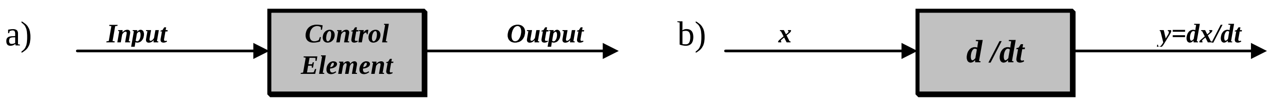

Fig. 2-2

The operations of addition and subtraction have a special representation. The block becomes a small circle, called a ***summing point***, with the appropriate plus or minus sign associated with the arrows entering the circle. The output is the algebraic sum of the inputs. Any number of inputs may enter a summing point.

Example 2.2

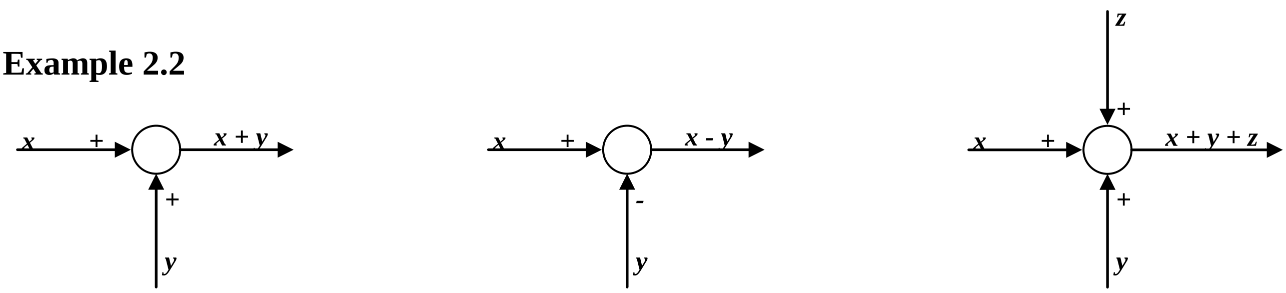

Fig. 2-3

Some authors put a cross in the circle: (Fig. 2-4)

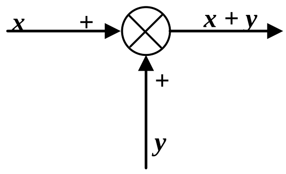

Fig. 2-4

This notation is avoided here because it is sometimes confused with the multiplication operation. In order to have the same signal or variable be an input to more than one block or summing point, a ***takeoff point*** is used. This permits the signal to proceed unaltered along several different paths to several destinations.

Example 2.3

Fig. 2-5

2.2 Block Diagrams Of Continuous (Analog) Feedback Control Systems

The blocks representing the various components of a control system are connected in a fashion which characterizes their functional relationships within the system. The basic configuration of a simple closed-loop (feedback) control system with a single input and a single output (abbreviated SISO) is illustrated in Fig. 2-6 for a system with continuous signals only.

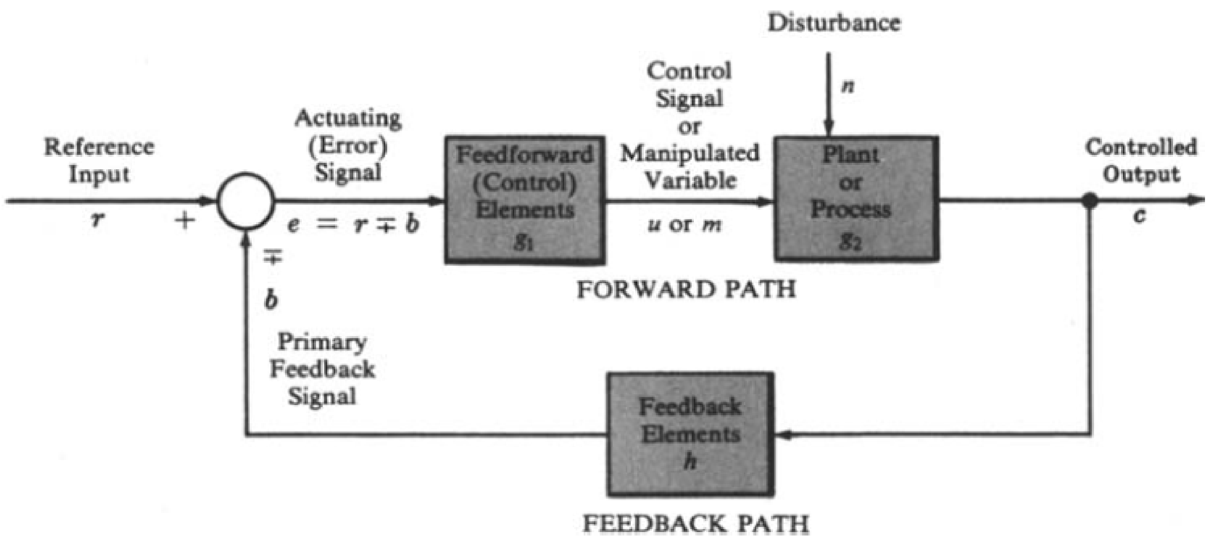

Fig. 2-6

We emphasize that the arrows of the closed loop, connecting one block with another, represent the direction of flow of control energy or information, which is not usually the main source of energy for the system. For example, the major source of energy for the thermostatically controlled furnace of Example 1.2 is often chemical, from burning fuel oil, coal, or gas. But this energy source would not appear in the closed control loop of the system.

2.3 Terminology Of The Closed-Loop Block Diagram

It is important that the terms used in the closed-loop block diagram be clearly understood. Lowercase letters are used to represent the input and output variables of each element as well as the symbols for the blocks g_1, g_2, and h. These quantities represent functions of time, unless otherwise specified.

1. The ***plant*** (or ***process***, or ***controlled system***) g_2 is the system, subsystem, process, or object controlled by the feedback control system.

2. The ***controlled output c*** is the output variable of the plant, under the control of the feedback control system.

3. The ***forward path*** is the transmission path from the summing point to the controlled output.

4. The ***feedforward (control) elements*** g_1 are the components of the forward path that generate the control signal u or m applied to the plant. Note: Feedforward elements typically include controller(s), compensator(s) (or equalization elements), and/or amplifiers.

5. The ***control signal u*** (or ***manipulated variable m***) is the output signal of the feedforward elements g_1 applied as input to the plant g_2.

6. The ***feedback path*** is the transmission path from the controlled output c back to the summing point.

7. The ***feedback elements h*** establish the functional relationship between the controlled output c and the primary feedback signal b. Note: Feedback elements typically include sensors of the controlled output c, compensators, and/or controller elements.

8. The ***reference input r*** is an external signal applied to the feedback control system, usually at the first summing point, in order to command a specified action of the plant. It usually represents ideal (or desired) plant output behavior.

9. The ***primary feedback signal b*** is a function of the controlled output c, algebraically summed with the reference input r to obtain the actuating (error) signal e , that is, r f b = e. Note: An open-loop system has no primary feedback signal.

10. The ***actuating*** (or ***error***) ***signal*** is the reference input signal r plus or minus the primary feedback signal b. The control action is generated by the actuating (error) signal in a feedback control system. Note: In an open-loop system, which has no feedback, the actuating signal is equal to r .

11. ***Negative feedback*** means the summing point is a subtractor, that is, e = r - b.

12. ***Positive feedback*** means the summing point is an adder, that is, e = r + b.

2.4 Block Diagrams Of Discrete-Time (Sampled-Data, Digital) Components, Control Systems, And Computer-Controlled Systems

A discrete-time (sampled-data or digital) control system was defined in Definition 1.11 as one having discrete-time signals or components at one or more points in the system. We introduce several common discrete-time system components first, and then illustrate some of the ways they are interconnected in digital control systems. We remind the reader here that discrete-time is often abbreviated as discrete in this book, and continuous-time as continuous, wherever the meaning is unambiguous.

Example 2.4
A digital computer or microprocessor is a discrete-time (discrete or digital) device, a common component in digital control systems. The internal and external signals of a digital computer are typically discrete-time or digitally coded.

Example 2.5
A discrete system component (or components) with discrete-time input $u(t_k)$ and discrete-time output $y(t_k)$ signals, where t_k are discrete instants of time, k = 1,2,. . . , etc., may be represented by a block diagram, as shown in Fig. 2-7.

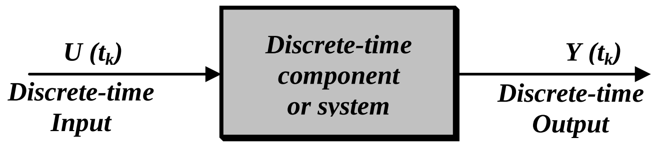

Fig. 2-7

Many digital control systems contain both continuous and discrete components. One or more devices known as samplers, and others known as holds, are usually included in such systems.

A ***sampler*** is a device that converts a continuous-time signal, say $u(t)$, into a discrete-time signal, denoted $u^*(t)$, consisting of a sequence of values of the signal at the instants t_1, t_2, ..., that is, $u(t_1)$, $u(t_2)$, ..., etc.

0 samplers are usually represented schematically by a switch, as shown in Fig. 2-8, where the switch is normally open except at the instants t_1, t_2, ..., etc., when it is closed for an instant. The switch also may be represented as enclosed in a block, as shown in Fig. 2-9.

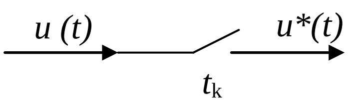

Fig. 2-8

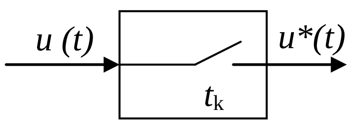

Fig. 2-9

Example 2.6

The input signal of an ideal sampler and a few samples of the output signal are illustrated in Fig. 2-10. This type of signal is often called a sampled-data signal.

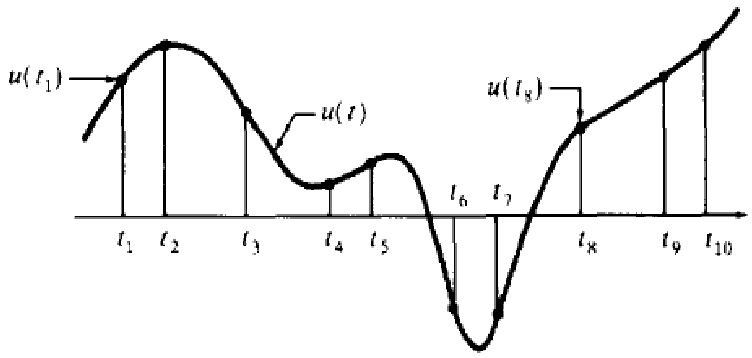

Fig. 2-10

Discrete-data signals $u(t_k)$ are often written more simply with the index k as the only argument, that is, $u(k)$, and the sequence $u(t_1)$, $u(t_2)$, ..., etc., becomes $u(l)$, $u(2)$, …, etc. This notation is introduced in Chapter 3. Although sampling rates are in general non uniform, as in Example 2.6, uniform sampling is the rule in this book, that is, $t_{k+1} – t_k = T$ for all k.

A ***hold***, or ***data hold***, device is one that converts the discrete-time output of a sampler into a particular kind of continuous-time or analog signal.

Example 2.7

A ***zero-order hold*** (or ***simple hold***) is one that maintains (i.e., holds) the value of $u(t_k)$ constant until the next sampling time t_{k+1}, as shown in Fig. 2-11. Note that the output $y_{HO}(t)$ of the zero-order hold is continuous, except at the sampling times. This type of signal is called a piecewise-continuous signal.

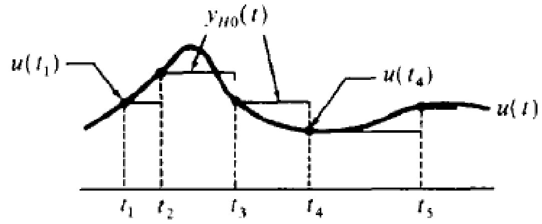

Fig. 2-11

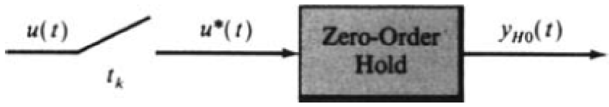

Fig. 2-12

An ***analog-to-digital (A/D) converter*** is a device that converts an analog or continuous signal into a discrete or digital signal.

A ***digital-to-analog (D/A) converter*** is a device that converts a discrete or digital signal into a continuous- time or analog signal.

Example 2.8

The sampler in Example 2.6 (Figs. 2-9 and 2-10) is an A/D converter

Example 2.9

The zero-order hold in Example 2.7 (Figs. 2-11 and 2-12) is a D/A converter.

Samplers and zero-order holds are commonly used A/D and D/A converters, but they are not the only types available. Some D/A converters, in particular, are more complex.

Example 2.10

Digital computers or microprocessors are often used to control continuous plants or processes. A/D and D/A converters are typically required in such applications, to convert signals from the plant to digital signals, and to convert the digital signal from the computer into a control signal for the analog plant. The joint operation of these elements is usually synchronized by a clock and the resulting controller is sometimes called a ***digital filter***, as illustrated in Fig. 2-13.

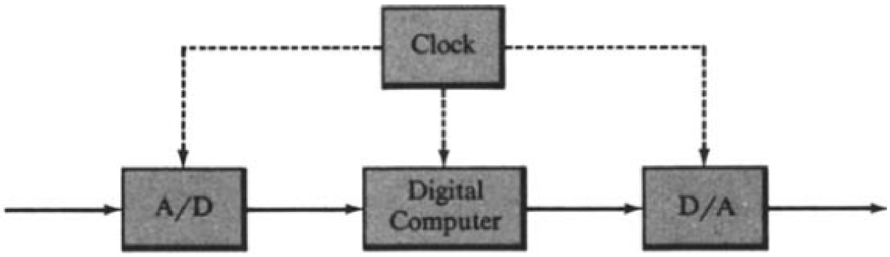

Fig. 2-13

A ***computer-controlled system*** includes a computer as the primary control element.

The most common computer-controlled systems have digital computers controlling analog or continuous processes. In this case, A/D and D/A converters are needed, as illustrated in Fig. 2-14.

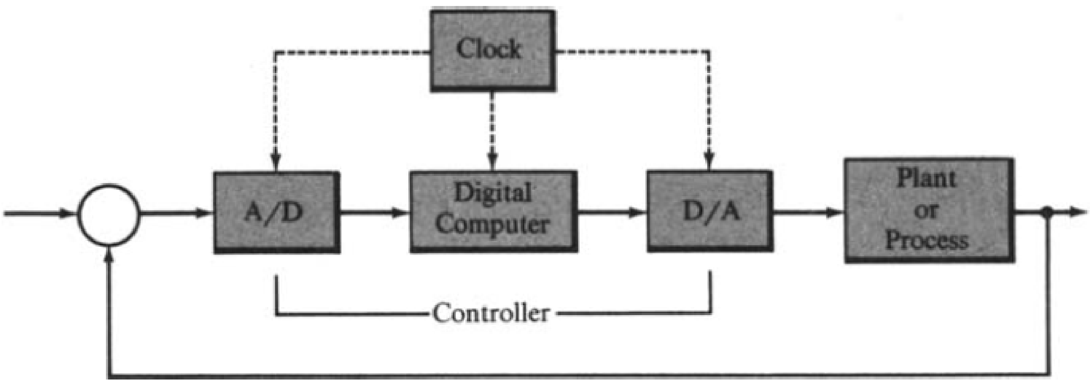

Fig. 2-14

The clock may be omitted from the diagram, as it synchronizes but is not an explicit part of signal flow in the control loop. Also, the summing junction and reference input are sometimes omitted from the diagram, because they may be implemented in the computer.

2.5 Supplementary Terminology

Several other terms require definition and illustration at this time. Others are presented in subsequent chapters, as needed.

A ***transducer*** is a device that converts one energy form into another

For example, one of the most common transducers in control systems applications is the ***potentiometer***, which converts mechanical position into an electrical voltage (Fig. 2-15).

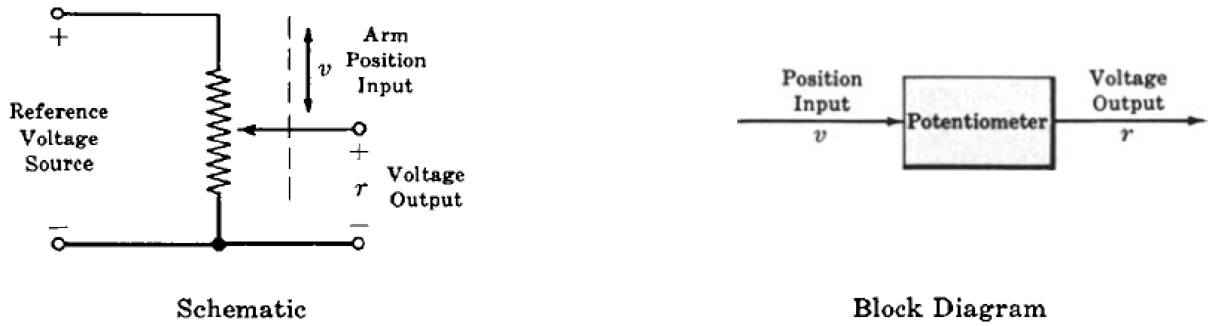

Fig. 2-15

The command ***v*** is an input signal, usually equal to the reference input ***r***. But when the energy form of the command ***v*** is not the same as that of the primary feedback b, a transducer is required between the command ***v*** and the reference input ***r*** as shown in Fig. 2-16(a).

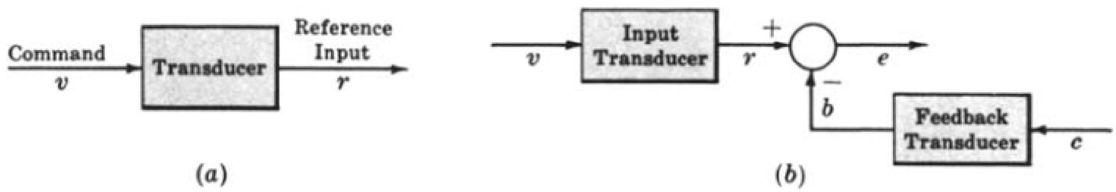

Fig. 2-16

When the feedback element consists of a transducer, and a transducer is required at the input, that part of the control system illustrated in Fig. 2-16(b) is called the ***error detector***.

A ***stimulus***, or ***test input***, is any externally (exogenously) introduced input signal affecting the controlled output ***c***. Note: The reference input ***r*** is an example of a stimulus, but it is not the only kind of stimulus.

A ***disturbance n*** (or ***noise input***) is an undesired stimulus or input signal affecting the value of the controlled output ***c***. It may enter the plant with ***u*** or ***m***, as shown in the block diagram of Fig. 2-6, or at the first summing point, or via another intermediate point.

The ***time response*** of a system, subsystem, or element is the output as a function of time, usually following application of a prescribed input under specified operating conditions.

A ***multivariable system*** is one with more than one input (***multiinput, MI***), more than one output (***multioutput, MO***), or both (***multiinput-multioutput, MIMO***).

The term ***Controller*** in a feedback control system is often associated with the elements of the forward path, between the actuating (error) signal e and the control variable ***u***. But it also sometimes includes the summing point, the feedback elements, or both, and some authors use the term controller and compensator synonymously. The context should eliminate ambiguity.

The following five definitions are examples of ***control laws***, or ***control algorithms***.

An ***on-off controller (two-position, binary controller)*** has only two possible values at its output ***u***, depending on the input ***e*** to the controller.

A ***proportional (P) controller*** has an output ***u*** proportional to its input ***e***, that is, $u = K_p e$, where ***K***, is a proportionality constant.

A ***derivative (D) controller*** has an output proportional to the derivative of its input ***e***, that is, $u = K_D\, de/dt$, where K_D is a proportionality constant.

An ***integral (I) controller*** has an output ***u*** proportional to the integral of its input e, that is, $U = K_I \int e(t)\,.dt$, where ***K***, is a proportionality constant.

PD, PI, DI, and PID controllers are combinations of ***proportional (P)***, ***derivative (D)***, and ***integral (I)*** controllers.

2.6 Servomechanisms

The specialized feedback control system called a servomechanism deserves special attention, due to its prevalence in industrial applications and control systems literature.

A ***servomechanism*** is a power-amplifying feedback control system in which the controlled variable ***c*** is mechanical position, or a time derivative of position such as velocity or acceleration.

Example 2.11
An automobile power-steering apparatus is a servomechanism. The command input is the angular position of the steering wheel. A small rotational torque applied to the steering wheel is amplified hydraulically, resulting in a force adequate to modify the output, the angular position of the front wheels. The block diagram of such a system may be represented by Fig. 2-17. Negative feedback is necessary in order to return the control valve to the neutral position, reducing the torque from the hydraulic amplifier to zero when the desired wheel position has been achieved.

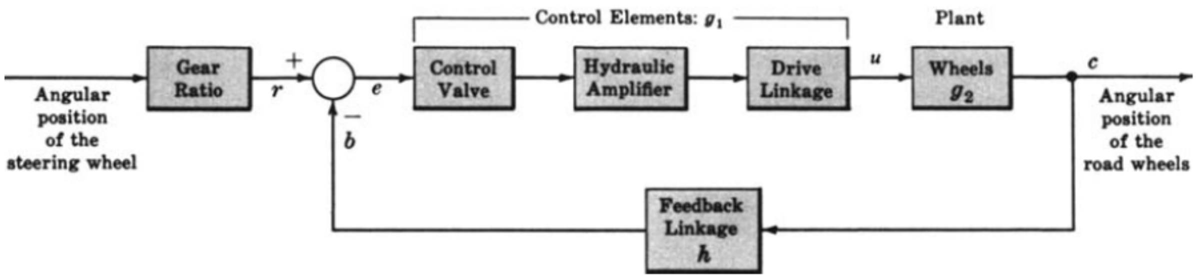

Fig. 2-17

2.7 <u>Regulators</u>

A ***regulator or regulating system*** is a feedback control system in which the reference input or command is constant for long periods of time, often for the entire time interval during which the system is operational. Such an input is often called a ***setpoint***.

A regulator differs from a servomechanism in that the primary function of a regulator is usually to maintain a constant controlled output, while that of a servomechanism is most often to cause the output of the system to follow a varying input.