CHAPTER ONE

INTRODUCTION

1.1. ***Control Systems:***

In modern usage the word *system* has many meanings. So let us begin by defining what we mean when we use this word in this book, first abstractly then slightly more specifically in relation to scientific literature.

A system is an arrangement, set, or collection of things connected or related in such a manner as to form an entirety or whole.

A system is an arrangement of physical components connected or related in such a manner as to form and/or act as an entire unit.

The word *control* is usually taken to mean *regulate, direct,* or *command.* Combining the above definitions, we have

A control system is an arrangement of physical components connected or related in such a manner as to command, direct, or regulate itself or another system.

In the most abstract sense it is possible to consider every physical object a control system. Everything alters its environment in some manner, if not actively then passively-like a mirror *directing* a beam of light shining on it at some acute angle. The mirror (Fig. 1-1) may be considered an elementary control system, controlling the beam of light according to the simple equation "the angle of reflection *a* equals the angle of incidence *a.*"

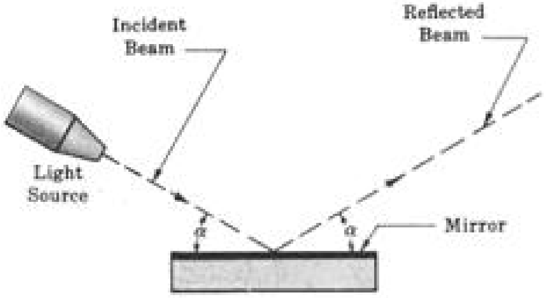

Fig. 1-1

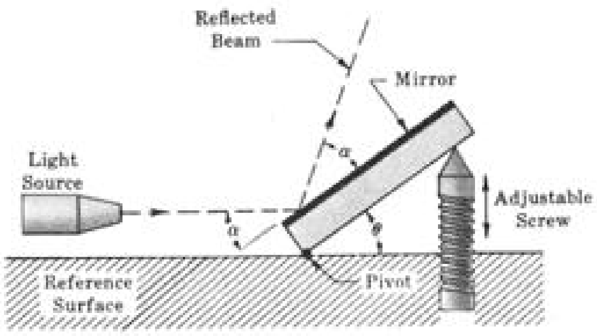

Fig. 1-2

In engineering and science we usually restrict the meaning of control systems to apply to those systems whose major function is to *dynamically* or *actively* command, direct, or regulate. The system shown in Fig. 1-2, consisting of a mirror pivoted at one end and adjusted up and down with a screw at the other end, is properly termed a *control system.* The angle of reflected light is regulated by means of the screw.

It is important to note, however, that control systems of interest for analysis or design purposes include not only those manufactured by humans, but those that normally exist in nature, and control systems with both manufactured and natural components.

1.2. Examples Of Control Systems

Control systems abound in our environment. But before exemplifying this, we define two terms: input and output, which help in identifying, delineating, or defining a control system.

The input is the stimulus, excitation or command applied to a control system, typically from an external energy source, usually in order to produce a specified response from the control system.

The output is the actual response obtained from a control system. It may or may not be equal to the specified response implied by the input.

Inputs and outputs can have many different forms. Inputs, for example, may be physical variables, or more abstract quantities such as reference, set point, or desired values for the output of the control system.
The purpose of the control system usually identifies or defines the output and input. If the output and input are given, it is possible to identify, delineate, or define the nature of the system components.
Control systems may have more than one input or output. Often all inputs and outputs are well defined by the system description. But sometimes they are not. For example, an atmospheric electrical storm may intermittently interfere with radio reception, producing an unwanted output from a loudspeaker in the form of static. This “noise” output is part of the total output as defined above, but for the purpose of simply identifying a system, spurious inputs producing undesirable outputs are not normally considered as inputs and outputs in the system description. However, it is usually necessary to carefully consider these extra inputs and outputs when the system is examined in detail.
The terms input and output also may be used in the description of any type of system, whether or not it is a control system, and a control system may be part of a larger system, in which case it is called a *subsystem* or *control subsystem*, and its inputs and outputs may then be internal variables of the larger system.

Example 1.1.
An electric switch is a manufactured control system, controlling the flow of electricity. By definition, the apparatus or person flipping the switch is not a part of this control system.
Flipping the switch on or off may be considered as the input. That is, the input can be in one of two states, on or off. The output is the flow or no flow (two states) of electricity.
The electric switch is one of the most rudimentary control systems.

Example 1.2.
A thermostatically controlled heater or furnace automatically regulating the temperature of a room or enclosure is a control system. The input to this system is a reference temperature, usually specified by appropriately setting a thermostat. The output is the actual temperature of the room or enclosure.
When the thermostat detects that the output is less than the input, the furnace provides heat until the temperature of the enclosure becomes equal to the reference input. Then the furnace is automatically turned off. When the temperature falls somewhat below the reference temperature, the furnace is turned on again.

Example 1.3.
The seemingly simple act of *pointing at an object with a finger* requires a biological control system consisting chiefly of the eyes, the arm, hand and finger, and the brain. The input is the precise direction of the object (moving or not) with respect to some reference, and the output is the actual pointed direction with respect to the same reference.

Example 1.4.
A part of the human temperature control system is the *perspiration system*. When the temperature of the air exterior to the skin becomes too high the sweat glands secrete heavily, inducing cooling of the skin by evaporation. Secretions are reduced when the desired cooling effect is achieved, or when the air temperature falls sufficiently.
The input to this system may be "normal" or comfortable skin temperature, a "setpoint," or the air temperature, a physical variable. The output is the actual skin temperature.

Example 1.5.
The control system consisting of a person driving an automobile has components which are clearly both manufactured and biological. The driver wants to keep the automobile in the appropriate lane of the roadway. He or she accomplishes this by constantly watching the direction of the automobile with respect to the direction of the road. In this case, the direction or heading of the road, represented by the painted guide line or lines on either side of the lane may be considered as the input. The heading of the automobile is the output of the system. The driver controls this output by constantly measuring it with his or her eyes and brain, and correcting it with his or her hands on the steering wheel. The major components of this control system are the driver's hands, eyes and brain, and the vehicle.

1.3 Open-Loop and Closed-Loop Control Systems

Control systems are classified into two general categories: open-loop and closed-loop systems. The distinction is determined by the *control action*, that quantity responsible for activating the system to produce the output.
The term *control action* is classical in the control systems literature, but the word action in this expression does not always directly imply change, motion, or activity. For example, the control action in a system designed to have an object hit a target is usually the distance between the object and the target. Distance, as such, is not an action, but action (motion) is implied here, because the goal of such a control system is to reduce this distance to zero.

An open-loop control system is one in which the control action is independent of the output.

A closed-loop control system is one in which the control action is somehow dependent on the output.

Two outstanding features of open-loop control systems are:
1. Their ability to perform accurately is determined by their calibration. To calibrate means to establish or reestablish the input-output relation to obtain desired system accuracy.
2. They are not usually troubled with problems of instability, a concept to be subsequently discussed in detail.

Closed-loop control systems are more commonly called feedback control systems, and are considered in more detail beginning in the next section.
To classify a.contro1 system as open-loop or closed-loop, we must distinguish clearly the components of the system from components that interact with but are not part of the system. For example, the driver in Example 1.5 was defined as part of that control system, but a human operator may or may not be a component of a system.

Example 1.6.
Most ***automatic toasters*** are open-loop systems because they are controlled by a timer. The time required to make ‘‘good toast” must be estimated by the user, who is not part of the system. Control over the quality of toast (the output) is removed once the time, which is both the input and the control action, has been set. The time is typically set by means of a calibrated dial or switch.

Example 1.7.
An autopilot mechanism and the airplane it controls is a closed-loop (feedback) control system. Its purpose is to maintain a specified airplane heading, despite atmospheric changes. It performs this task by continuously measuring the actual airplane heading, and automatically adjusting the airplane control surfaces (rudder, ailerons, etc.) so as to bring the actual airplane heading into correspondence with the specified heading. The human pilot or operator who presets the autopilot is not part of the control system.

1.4 Feedback

Feedback is that characteristic of closed-loop control systems which distinguishes them from open-loop systems.

Feedback is that property of a closed-loop system which permits the output (or some other controlled variable) to be compared with the input to the system (or an input to some other internally situated component or subsystem) so that the appropriate control action may be formed as some function of the output and input.

More generally, feedback is said to exist in a system when a closed sequence of cause-and-effect relations exists between system variables.

Example 1.8.
The concept of feedback is clearly illustrated by the autopilot mechanism of Example 1.7. The input is the specified heading, which may be set on a dial or other instrument of the airplane control panel, and the output is the actual heading, as determined by automatic navigation instruments. A comparison device continuously monitors the input and output. When the two are in correspondence, control action is not required. When a difference exists between the input and output, the comparison device delivers a control action signal to the controller, the autopilot mechanism. The controller provides the appropriate signals to the control surfaces of the airplane to reduce the input-output difference. Feedback may be effected by mechanical or electrical connections from the navigation instruments, measuring the heading, to the comparison device. In practice, the comparison device may be integrated within the autopilot mechanism.

1.5 Characteristics of Feedback

The presence of feedback typically imparts the following properties to a system.

1. Increased accuracy. For example, the ability to faithfully reproduce the input. This property is illustrated throughout the text.
2. Tendency toward oscillation or instability.
3. Reduced sensitivity of the ratio of output to input to variations in system parameters and other characteristics.
4. Reduced effects of nonlinearities.
5. Reduced effects of external disturbances or noise.
6. Increased bandwidth. The bandwidth of a system is a frequency response measure of how well the system responds to (or filters) variations (or frequencies) in the input signal.

1.6 Analog and Digital Control Systems

The signals in a control system, for example, the input and the output waveforms, are typically functions of some independent variable, usually time, denoted t.

A signal dependent on a continuum of values of the independent variable t is called a *continuous-time* signal or, more generally, a *continuous-data* signal or (less frequently) an *analog* signal.

A signal defined at, or of interest at, only discrete (distinct) instants of the independent variable t (upon which it depends) is called a *discrete-time*, a *discrete data*, a *sampled-data*, or a *digital* signal.

We remark that digital is a somewhat more specialized term, particularly in other contexts. We use it as a synonym here because it is the convention in the control systems literature.

Example 1.9.
The continuous, sinusoidally varying voltage $v(t)$ or alternating current $i(t)$ available from an ordinary household electrical receptable is a continuous-time (analog) signal, because it is defined at *each and every instant* of time t electrical power is available from that outlet.

Example 1.10.
If a lamp is connected to the receptacle in Example 1.9 and it is switched on and then immediately off every minute, the light from the lamp is a discrete-time signal, on only for an instant every minute.

Example 1.11.
The mean temperature T in a room at precisely 8 A.M. (08 hours) each day is a discrete-time signal. This signal may be denoted in several ways, depending on the application; for example T(8) for the temperature at 8 o'clock-rather than another time; T(l), *T(2)*,. . . for the temperature at 8 o'clock on day 1, day 2, etc., or, equivalently, using a subscript notation, T_1, T_{21}, etc. Note that these discrete-time signals are *sampled* values of a continuous-time signal, the mean temperature of the room at all times, denoted $T(t)$.

Example 1.12.
The signals inside digital computers and microprocessors are inherently discrete-time, or discrete-data, or digital (or digitally coded) signals. At their most basic level, they are typically in the form of sequences of voltages, currents, light intensities, or other physical variables, at either of two constant levels, for example, ±15 V; light-on, light-off; etc. These *binary signals* are usually represented in alphanumeric form (numbers, letters, or other characters) at the inputs and outputs of such digital devices. On the other hand, the signals of analog computers and other analog devices are continuous-time.

Control systems can be classified according to the types of signals they process: continuous-time (analog), discrete-time (digital), or a combination of both (hybrid).

Continuous-time control systems, also called *continuous-data control systems,* or *analog control systems,* contain or process only continuous-time (analog) signals and components.

Discrete-time control systems, also called *discrete-data control systems,* or *sampled data control systems,* have discrete-time signals or components at one or more points in the system.

We note that discrete-time control systems can have continuous-time as well as discrete-time signals; that is, they can be hybrid. The distinguishing factor is that a discrete-time or digital control system *must* include at least one discrete-data signal. Also, digital control systems, particularly of sampled-data type, often have both open-loop and closed-loop modes of operation.

Example 1.13.
A target tracking and following system, such as the one described in Example 1.3 (tracking and pointing at an object with a finger), is usually considered an analog or continuous-time control system, because the distance between the "tracker" (finger) and the target is a continuous function of time, and the objective of such a control system is to *continuously* follow the target. The system consisting of a person driving an automobile (Example 1.5) falls in the same category. Strictly speaking, however, tracking systems, both natural and manufactured, can have digital signals or components. For example, control signals from the brain are often treated as "pulsed" or discrete-time data in more detailed models which include the brain, and digital computers or microprocessors have replaced many analog components in vehicle control systems and tracking mechanisms.

Example 1.14.
A closer look at the thermostatically controlled heating system of Example 1.2 indicates that it is actually a sampled-data control system, with both digital and analog components and signals. If the desired room temperature is, say, 68°F (22°C) on the thermostat and the room temperature falls below, say, 66°F, the thermostat switching system closes the circuit to the furnace (an analog device), turning it on until the temperature of the room reaches, say, 70°F. Then the switching system automatically turns the furnace off until the room temperature again falls below 66°F. This control system is actually operating open-loop between switching instants, when the thermostat turns the furnace on or off, but overall operation is considered closed-loop. The thermostat receives a continuous-time signal at its input, the actual room temperature, and it delivers a discrete-time (binary) switching signal

at its output, turning the furnace on or off. Actual room temperature thus varies continuously between 66° and 70°F, and means temperature is controlled at about 68°F, the *setpoint* of the thermostat.

The terms discrete-time and discrete-data, sampled-data, and continuous-time and continuous-data are often abbreviated as discrete, sampled, and continuous in the remainder of the book, wherever the meaning is unambiguous. Digital or analog is also used in place of discrete (sampled) or continuous where appropriate and when the meaning is clear from the context.