1

Introduction

The complexity of the problems of man's existence is growing at an ever-increasing rate and it may be expected to continue to do so in future. As such, constantly, human effort and capacity is replaced by machines and control systems, wherever possible, so that these may be employed to other problems, where it is indispensable.

It is indeed not surprising that such replacements perform the job more efficiently than their human counterpart. These machines or processes are not susceptible to so much fatigue or as many blunders and errors as human beings are. Moreover, they may operate at relatively high speed and precision and can be designed with very little difficulty. This fact that, the machine can compete and miserably beat its human counterpart in some specific jobs, is indeed often embarrassing to the common man. This however should not be so alarming, because it is not yet possible to duplicate a human brain completely. Consequently, there are and will remain many facets of life where human intervention and effort would be indispensable. Such systems and automation will therefore only increase the capability of human being and his horizon of activity.

For the past few decades, the trend of the modern civilization have been in the direction of greater control. Its importance has grown tremendously in almost every field of technical endeavour. Thermostats regulate the temperature in air-conditioners, refrigerators, ovens and furnaces. Numerous control arrangements find their ways into industrial and military applications, for the control of quantities, such as position, speed, tension, temperature, humidity, presssure flow etc. Some specific examples are—tension controllers of sheet rolls in paper mills, thickness controllers of sheet metals in rolling mills, pressure controllers in boilers, concentration controllers, reaction controllers etc., in chemical processes, radar, antenna sweeping control, gun director, missile control and control in space etc.

Complex living has demanded automation of large-scale problems ; thus for example, transportation problems concerning dispatching, switching and signalling in rail roads, reservation system for air passengers, air traffic and landing systems etc. have been partly or fully automated.

With the limited supply of natural resources and keen competition in allied business, one of the burning problems of the day is that of optimization of cost and material. Thus the electric power generation scheduling is automated to reduce cost. Plant managers seek ways and means to schedule his plant operation to maximize production and profit. Rocket engineer designs his rocket control arrangement to place the satellite in a desired orbit or send a space craft on a mission with a specific pay load requiring minimum fuel.

Recent efforts in the area of wather prediction, hand-written character recognition, medical diagnosis and other types of pattern recognition deal with the most sophisticated type of control systems, known as learning systems.

1·1. Concept of a System

Before the concept of control system is introduced, it is desirable to discuss the essential features of a system. This is what we shall do in what follows. A more formal treatment will be given later.

A system is a co-ordinated unit of individual elements performing a specific function. It produces an output corresponding to a given input according to some rule. Thus, electrical, mechanical, hydraulic, pneumatic, chemical, analog, digital etc. or any other elements, devices or processes and/or interacting combinations thereof may be regarded as systems.

When, at least one element or member of a system is capable of storing energy or some similar capacity, such a system is known to be dynamic. In such systems one or more aspects or states give a lagging response, following an input. This means that the states pass through a transient condition before their arrive at their respective steady state values.

Some specific examples may help to illustrate the point.

EXAMPLES

A Thermometer. Consider the action of temperature upon a thermometer. We know that the length of the mercury column is directly dependent upon the temperature around the mercury bulb. We may identify the thermometer as a system whose input $u=\theta$ is the temperature and the output $x=l$ is the length of the mercury thread

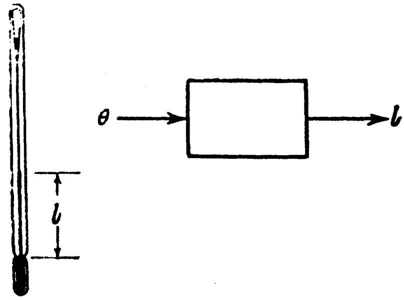

Fig. 1·1·1. A thermometer.

in the capillary tube. Here we have a case of a single-input-single-output system. This is shown in Fig. 1·1-1. Evidently, when the input is a step change in temperature, the output length l cannot change immediately to its steady state value. On the contrary it arrives at this value through a transient condition.

A Mechanical System. Consider the elementary spring-mass-damper system as shown in Fig. 1·1-2, subjected to an input force. Here we might be interested in considering the position of the mass as output and the force as input to the system.

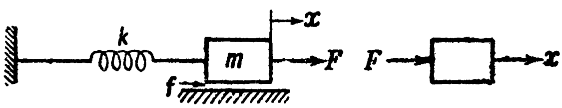

Fig. 1·1-2. A mechanical system.

Thermostat Controlled Room Heater Fig. 1·1-3 shows a schematic diagram of a room heating system with thermostat control arrangement. The position u of the set-screw SS determines the resting position of the bimetallic spring. When the power switch is on

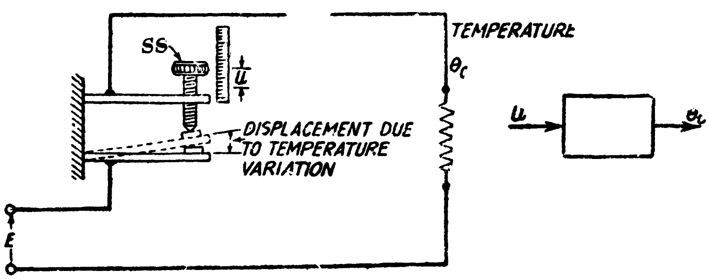

Fig. 1·1-3. A temperature controlling system.

and the room temperature is sufficiently low, the contact rests on the set-screw, and the heater is on. It remains switched on till such time as the temperature increases beyond a specific value of the room temperature and hence the bimetallic strip temperature θ. When this temperature is exceeded the strip pulls itself away from the initial position, thus breaking the contact. As the heater is switched off, the room temperature starts falling and eventually the bimetallic strip establishes the contact again while cooling down. Thus a sequence of room heating and cooling is in operation maintaining an average room temperature θ_0 corresponding to the set-screw position u. A change in u will indeed change θ_0 according to some rule. Thus this room heating arrangement may be considered as a system with u as an input and θ_0 as an output. This is again a case of a single-input-single-output system.

An Electric Network. A convenient example of a multiple-input-multiple-output system is that of a multiloop electric network as shown in Fig. 1·1-4, where several source voltages E_1, E_2, E_3 may be considered as the inputs and several resulting currents I_1, I_2,...I_6,

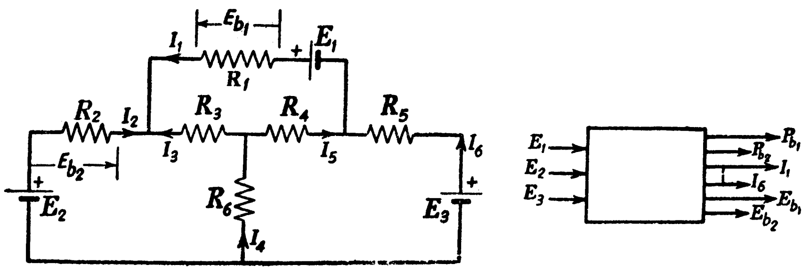

Fig. 1·1-4. An electric network.

branch voltages E_{b1}, E_{b2}, ..., power consumptions P_{b1}, P_{b2},... etc., may be considered as the output quantities.

1·2. Choice of Input Variables

It should be noted that the choice of input and output is often arbitrary. It essentially depends upon the point of view one wishes to take in regard to a system. For instance, consider the example of the mechanical system. One might consider the velocity as the output, instead of the position.

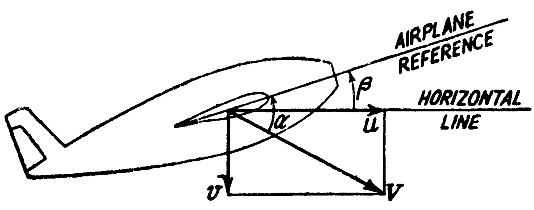

Fig. 1·2-1. An aircraft while descending.

Again when we consider the landing of an aircraft, shown in Fig. 1·2-1 with a motion in one plane, the input is the elevator deflection δ. One may be interested in studying the displacement of the C.G. of the airplane, hence may consider the horizontal and the vertical components u and v of the velocity V, as shown in Fig. 1·2-2. If on the other hand, one is interested in the angular

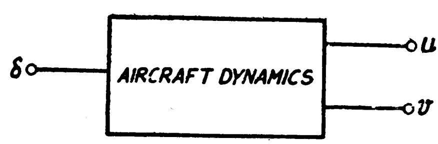

Fig. 1·2-2. The aircraft system as a single-input-two-out-put system.

positions of the airplane reference, α and β, *i.e.* its attitude* with respect to the actual velocity V and the horizontal respectively then the system is considered as shown in Fig. 1·2-3 with the two outputs α and β.

Fig. 1·2-3. The aircraft system as still another single input-two-output system.

It is sometimes necessary to study single-input-single-output characteristic of a multiple-input-multiple-output system. This may be done by keeping all but one input variable fixed and recording the behaviour of one output only.

Consider, as an example, a chemical mixing plant as shown in Fig. 1·2-4. In this plant a concentrated acid at a fixed concentration

Fig. 1·2-4. A chemical mixing plant considered as a two-input-two-output system.

c_a is diluted with water to produce acid at lower concentration c_o. If the flow rate of the incoming acid be q_a, flow rate of incoming water be q_w and the concentratin of the outgoing acid be c_o as shown then, essentially the plant may be looked upon as a two-input-two-output plant.

We might however be interested in examining how the output concentration c_o behaves with changes in *only* the flow rate of the concentrated acid q_a at fixed flow rate q_w of water. Our point of view thus focuses upon a single-input-single-output arrangement of a more complex multiple-input-multiple-output plant. This is shown in Fig. 1·2-5. Note that if we feed the acid at a variable concentra-

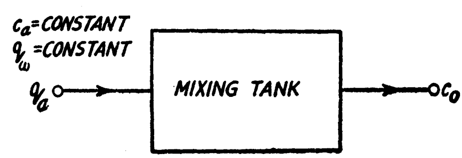

Fig. 1·2-5. The mixing plant considered as a single-input-single-output system.

***By attitude of a body is meant, the angular orientation of it with respect to the three dimensional reference frame.**

tion c_a we then have a three-input-two-output system as shown in Fig. 1·2-6.

Fig. 1·2-6. The mixing plant considered as a three-input-two-output system.

It may be noted that all the examples of systems may be classified as dynamic systems except for the example of the electric network, where all the elements of such a network is purely resistive.

A more formal treatment for systems will be given in a later section.

1·3. The Control System

A control system is, in general, a combination of elements or sub-systems which tends to maintain a quantity or a set of quantities termed output, suitably related to another quantity or a set of quantities termd input. The system is illustrated by the block diagram in Fig 1·3-1.

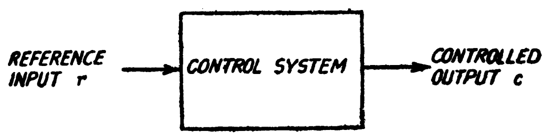

Fig. 1·3-1. A control system.

The reference input is essentially a signal or a set of signals in some form which acts upon the system in such a way that the response at the output takes place in a desired manner.

Control systems may be classified into two types depending upon whether the controlled variable affects the actual input to the control system or not, *i.e.* whether some kind of a feedback is used or not. When feed-back is not used, the system is called an open loop system, when used, it is called a closed loop system.

1·4. The Open Loop System

The open loop systems are by far the simplest and most economic type of control systems. However, these are generally inaccurate and unreliable and as such are not preferred. Often a system operating in the open loop may be structurally unstable and hence unacceptable in this form for any practical use.

In an open loop system an input known as reference input is applied directly to the controller (often through an amplifier), and an output known as controlled output is obtained. Here in an open loop system the input to the controller is in no way affected by the value of the controlled output. The input may be applied manually, by turning a dial. Such a system is schematically shown in the block diagram form as in Fig. 1·4-1 and Fig. 1·4-2.

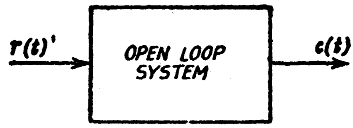

Fig. 1·4-1. Representation of an open loop system in block diagram.

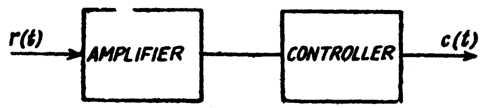

Fig. 1·4-2. Another block diagram representation of an open loop system.

In what follows, we will give a few examples of open loop systems and discuss in brief, their mode of operation.

EXAMPLES

Consider as an example, the case of a mixing tank in the operating mode shown in Fig. 1·2-5, *i.e.*, the input acid concentration c_a and the flow rate of water q_w are fixed. Naturally, the problem will be to control the output concentration c_0 by varying the flow rate q_a of the concentrated acid. It is easy to see that the, steady state value of c_0 could be set at some level by fixing q_a at a proper value.

It may indeed be possible, to make a calibration chart relating the steady-state output concentration c_0 to the acid input q_a. If such a chart is available, the output concentration c_0 may, at any later time be set at some desired level by setting the acid input at a corresponding value obtained from the chart.

Obviously however, should there be any fluctuation in the input concentration c_a or in the water input q_w, the output concentration c_0 will not remain at the desired preset level, even though c_a remained fixed throughout.

Again, consider as a second example, the case of a separately excited d.c. generator as shown in Fig. 1·4-3. Here a rotating amplifier such as an amplidyne or rototrol supplies power to the exciting field. A variation of the input ε to the rotating amplifier gives a proportional variation of the exciter voltage e_f. Consequently generator speed remaining constant, its generated voltage e_g also varies with ε. So does the output voltage e_0. Thus this constitutes

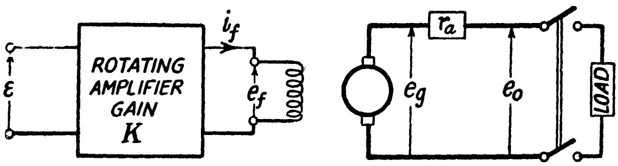

Fig. 1·4-3. A separately excited generator with rotating amplifier.

an open loop control system, where ε is the input and e_0 is the output. This relationship may be represented in the form of a block diagram

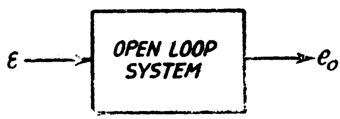

Fig. 1·4-4 Block diagram representation of the open loop system in Fig. 1·43.

shown in Fig 1·4-4.

Assuming rated load $P=P_l$ and fixed generator speed $n=n_1$, it is possible to obtain a calibration chart, which is of the form illustrated in Fig. 1·4-5. This relates steady-state output voltage e_0 with the input.

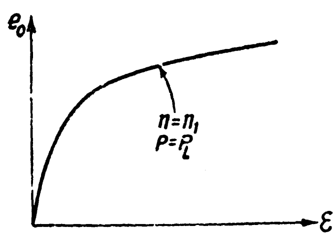

Fig. 1·4-5. Calibration chart for the system in Fig. 1·4-3.

Here again, fluctuation in the parameters, *i,e.*, generator speed, load etc. will result in output deviation. It should also be noted that in both the examples, such errors in the steady state due to variations in the system parameters, will almost always be preceded by some transients which, depending upon the sluggishness of the system may lead to an unacceptable error in the output. This transient however is to be expected, because both the systems are dynamic in nature. It is therefore clear that an open loop system may fail to give a desirable speed of response in a control situation and a closed loop system has to be designed.

So far, we have discussed examples of open loop systems which tend to stabilize in a finite steady-state value of output. Such systems are known to be stable in the open loop. There are, however, another class of systems, which are structurally unstable in the open loop and as such unacceptable in this form. Consider, as an example, the attitude of a rocket after blast off. Let it be desired that the attitude of the rocket be vertical as shown in Fig. 1·4-6. However, as the rocket motors generating the input thrust F are at the bottom, the system is mechanically in an unstable equilibrium. This may be easily verified from the fact that even if the thrust generated is acting precisely along a vertical line containing the C.G. of the rocket as shown, any slight perturbation will put the rocket off balance. Thus in this case, it is essential to provide a corrective thrust, whenever an error in the rocket attitude (in the vertical direction) grows beyond an acceptable value. The stability may be assured, by making a suitably "compensated" closed loop system out of it.

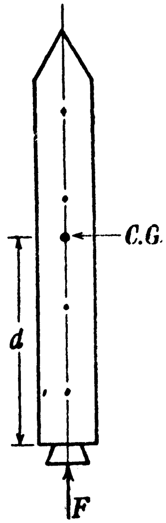

Fig. 1·4-6. A booster rocket.

1·5. Closed Loop System

In a closed loop control system, the corrective signal which drives the controller is derived from some kind of comparison between the input variable and the control variable. Thus in general, when a controller, which itself drives a plant*, is driven by some functions of a difference of the reference input r and a fraction of controlled output (usually this difference is termed as error), the overall system is known as a closed loop system. This is shown in block diagram in Fig 1·5-1. The function of the error-sensor or comparator in Fig 1·5-1 is to give an output ε which is equal to the reference input r minus the quentity $k_f c$ due to output c. Since this output is, in some form, a measure of error, this sub-system is known as an error-sensor or comparator, and it is the error which drives the plant to give an output. For this reason closed-loop control systems are known as error actuated systems.

In many cases (the input to the controller the output of which subsequently drives the plant) is directly proportional to the error ε. Such closed loop systems are known as proportional error systems.

* Often the controller in conjunction with the plant is designated as a process.

Since the cotuputing process involved in this error-sensor is that of subtraction of a quantity proportional to output, the system is said to have a negative feed-back and the fraction k_f in question is termed as feed-back factor. If in particular k_f is unity, the system is known to be a unity feed-back system.

The path starting just after the error-sensor to the output end is known as the forward path and the one starting from the output end to the error-sensor is known as the feed-back path.

As generally, the error or an odd function* of it actuates controller, the system essentially is a null-seeking device. The controller generally functions to correct the output so long as the error is non-zero and it stops functioning when the error is zero in the steady-state, *i.e.*, the controller stops acting when the null seeking is complete. Such a system automatically attempts to correct any discrepancy between input and output and thus is relatively independent of functions in system parameter.

When control systems are designed for the specific purpose of maintaining a correspondence between an output or controlled variable and an input or a reference variable under varying conditions of load, changes in the system parameter and other disturbances, while the input either remains at a constant value, or at most, changes relatively infrequently. Such a control system is known as a regulator. If the external disturbances are negligible, the regulator may be operated in the open loop. However, when such disturbances affect the output considerably, a closed loop system is designed.

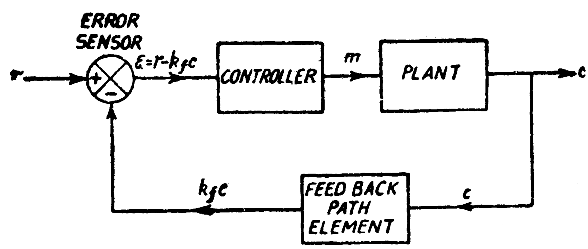

Fig. 1·5-1. A closed loop system with negative feed-back.

It should however be pointed out that a control system may have to perform a more onerous duty as will be evident later in this chapter. The output, for instance may be required to follow a continuously (or discontinuously) varying input as faithfully as possible.

When techniques of automatic control is applied to industrial processes involving factors such as rate of flow, variation of reaction

* A function is odd if $f(x)=-f(-x)$. Thus functions $f(x)=mx$, $=ax+bx^3+\ldots$, $=\sin x$ are odd,

rate, variation of temperature pressure, viscosity etc. it is usually termed process control. The basic principles in all such control systems however are essentially the same.

EXAMPLES

Human being as a control system. Feed-back control systems or processes are observed everywhere—in living organisms including human being, in automatic machines and processes, in organitions, in managements and in society. Of these, perhaps the most sophisticated and complex feedback control system is that of a human being, although with certain limitations in speed, accuracy and reliability.

Consider for instance the case of a person who is to push a door-bell. We will consider his action from his decision to reach the door-bell to the instant he reaches it. Obviously the reference input is the co-ordinates of the position of the door-bell, while the position of his particular finger to press the button is the output.* His eyes act as the error sensing device which continuously determine the distance of the finger from the door-bell and send *via* the controller, *i.e.*, the brain, signals to the power actuator, *i.e.*, the arm, which, by means of the motor action is lifted in a direction to reduce the error, *i.e.* the distance between the door-bell and the finger. The action continues till the error is zero. This is shown in the form of a block diagram in Fig 1·5-2. This is only one of the most simple jobs that a human being is capable of doing, and indeed many more such control operations may be performed by his system.

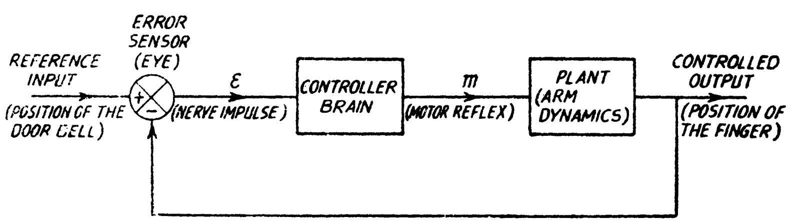

Fig. 1·5-2. The "human" feed-back control system.

A voltage regulating System. Consider as an example, the case of voltage regulating system. This system is shown schematically in Fig. 1·5-3.

In this arrangement the field of the customary separately excited generator is fed from the output of an amplifier with a gain k_A. The input ε of this amplifier is a voltage derived by subtracting $k_f\, e_o$, a fraction of the output e_o, from e_r. Thus

$$\varepsilon = e_r - k_f e_o \tag{1·5-1}$$

* Note that as the positions of the door-bell and the finger is in respect of a three dimensional space, the feed-back control system may in this instance be considered as a three-input-three-output system.

Here obviously the feed-back is negative because the feed-back quantity $k_f e_o$ is subtracted from the reference e_r to form the driving signal termed the error-ε. *See* R.H.S. of equation 1·5-1.

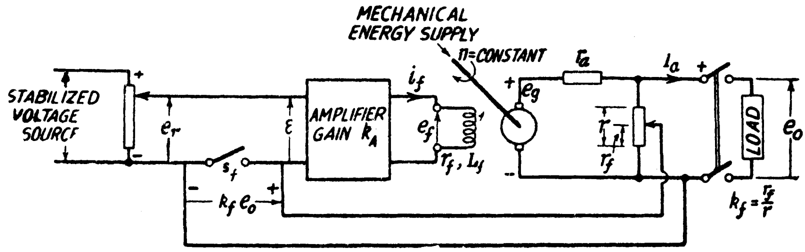

Fig. 1·5-3. A simple voltage control system.

To begin with, it is worthwhile to have an idea of how negtative feed-back affects system operation.

Let us suppose that the generator is giving an output e_o corresponding to a reference voltage e_r. Consequently the input ε is of such a value as to produce sufficient field current i_f which generates the right amount of generated voltage e_g, so that after subtracting from it, the $I_a r_a$ drop in the armature, we get the output voltage e_o. This is a sort of equilibrium condition which the system automatically establishes.

By providing a large overall gain, it is possible to obtain* a given output voltage e_o with a largely reduced amplifier input ε.

We now propose to upset the equilibrium condition by increasing e_o by an amount Δe_o.

This may be, for example due to increase of speed in the generator, decrease of load current, increase in the amplifier gain etc.

The increase Δe_o of the output voltage will increase the feed-back by an amount $k_f \Delta e_o$ from the equilibrium value of $k_f e_o$. Correspondingly the new input to the amplifier will be $\varepsilon - k_f \Delta e_o$. This will reduce in succession, the exciting voltage e_f, the exciting current i_f and the generator flux Φ. The output voltage will therefore reduce, by an amount Δe_g (say). Assuming negligible change in armature voltage drop $I_a r_a$, one may say the reduction Δe_g which in magnitude, is generaly less than Δe_o will tend to correct the increase Δe_o. Thus when balance is reached the system output will register a voltage of $e_o + \Delta e_o - \Delta e_g$. This is evidently better than the value $e_o + \Delta e_o$ at the output, whose constancy is desired. Although it is a fact that, Δe_g is always less than Δe_o in magnitude, but it can always be made reasonably close to Δe_o by suitable design.

*Increasing gain beyond limits has its disadvantages. This problem will be dealt with in a later section.

Just as, a tendency of an increase in e_0 is counteracted by a corresponding tendency to reduce the generated voltage, it is possible to show that a decrease in e_0 for the parameter variations is met with a tendency to increase the generated voltage, for a negative feed-back system. Thus the output voltage remains relatively unperturbed due to variations in the parameter. This feature of making a system relatively insensitive to certain parameter variations and internal noise is a fundamental useful characteristic of systems with negative feed-back.

It must however be mentioned now and will be shown in later discussions that the output voltage is indeed sensitive to input variation and also in any variation in the parameters of the feed-back path. The feed-back path should therefore be designed with such precision and stable components that there is neither much scope of parameter variation nor of any noise arising in the feedback path

Note that in this arrangement, the factor k_f may be adjusted and set to any value between 1 and 0. If k_f is set to zero, the voltage $k_f e_0$ becomes zero. Clearly, from Fig. 1·5-3, this condition may otherwise be obtained by closing the switch s_f. The system in this condition thus becomes an open loop system. A detailed study of this regulator is reserved for a later section.*

1·6. Basic Block Diagram of a Feed-back Control System

The general form of the block diagram of a feed-back control system is shown in Fig 1·6-1. The block diagram consists of a forward path containing a controller and a plant or a process, driven by the output of the error-sensor which compares a function of the output with the reference input. The function of the output is prescribed by the feed-back path element.

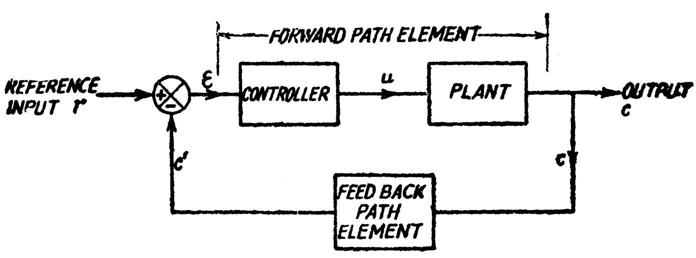

Fig. 1·6-1. Block diagram of a feed-back control system.

Often the controller may consist of a compensating network or system and an amplifier. In servo-systems, which are a class of feed-back control systems whose controlled outputs are mechanical quantities such as mechanical position, velocity etc., the plant may consist of an arrangement of motors and gears.

*Refer V. Del Toro & S.R. Parker, "Principles of Control System Engineering", McGraw Hill Book Company Inc., New York 1960, for some more such examples.

1·7. Levels of Sophistication in Control System

It is worth while to discuss the various levels of sophistication of control systems at this point. The most primitive of the control systems is of course the open loop control systems where any brute force is employed by some form of control with the error generally sensed by a human operator.

The next advancement was to replace the human operator from the job of error sensing. The loop was closed through some very stable physical system. This was the feed-back or closed loop system. The limitations of human error sensing was thus removed.

With the advent of high performance aircrafts missiles and space vehicles, the dynamic performance was found to vary drastically. Such systems needed parameter adjustments for desired performance. This added another stage of sophistication. Where control systems were required to "adapt" themselves to the changing environmental conditions.

The next higher stage of sophistication is achieved in, what is known as the learning systems. Such systems are designed to recognize familiar stimuli and pattern in an unknown situation. The major difference between an adaptive system and a learning system is that, while the former can cope with present situations, the latter is capable of recognizing new situations on the basis of its past experience, give decisions and act accordingly.

The four systems are shown in Fig 1·7-1 to Fig 1·7-4 respectively.

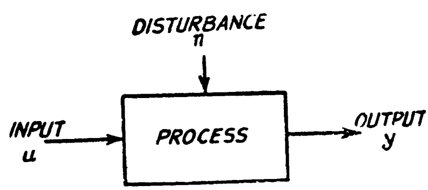

Fig. 1·7-1. Open loop System

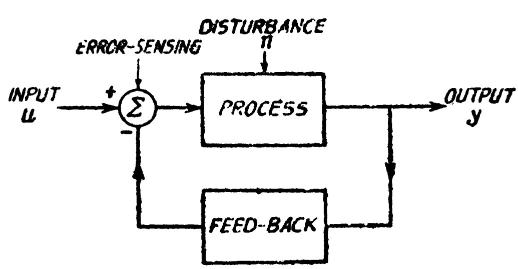

Fig. 1·7-2. Closed-loop System.

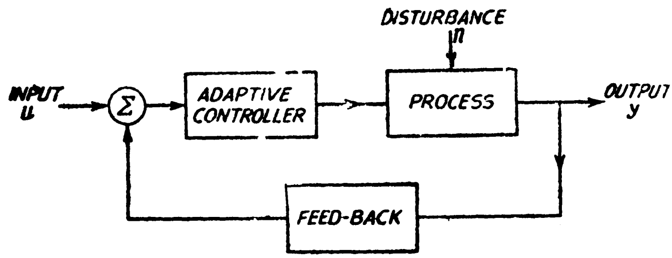

Fig. 1·7-3 Adaptive Controller.

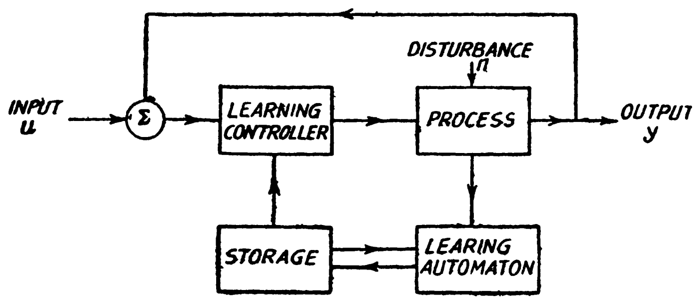

Fig. 1·7-4. Learning System.