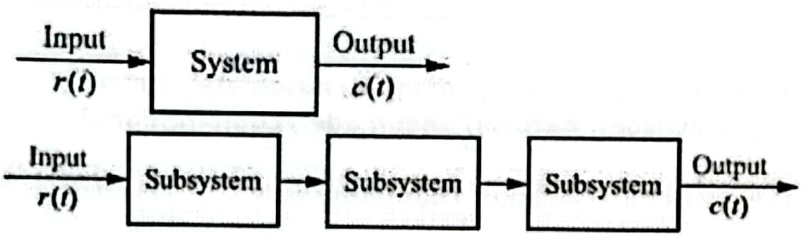
Introduction to control system Engineering
Lecture: 1~3

System: A system is a combination or an arrangement of different physical components which act together as an entire unit to achieve a certain objective.
A system is a collection, set, or arrangement of elements (subsystems). A kite is an example of a physical system because it is made of paper and sticks. A classroom and a lamp are also examples of the physical system.
Systems include physical, biological, organizational, and other entities, and combinations thereof, which can be represented through a common mathematical symbolism. The study of feedback control systems is essentially a study of an important aspect of systems engineering and its application.



$r(t)$: Reference input

$c(t)$: Controlled variable

Input:
- The input is the stimulus, excitation or command applied to a control system.
- The input is an applied signal or an excitation signal applied to a control system from an external energy source in order to produce a specified output.

Output:
- The output is the actual response obtained from a control system when an input is applied.
- It may or may not be equal to the specified response implied by the input.

Plant or Process: The portion of a system which is to be controlled or regulated is called the plant or the process.

Control: The meaning of control is to regulate, direct or command a system so that the desired object is obtained. Control is a set of technologies that achieve desired patterns of variations of operational parameters and sequences for machines and systems by providing the necessary input signals.
The control means to regulate, direct, command, or govern.

Controller: The element of the system itself or external to the system which controls the plant or the process is called a controller.

Control System: Control system is incorporation of different physical elements linked in such a manner so as to regulate, direct or command itself to obtain a certain objective. A control system is an interconnection of components forming a system configuration that will provide the desired system response. Hence, a control system is an arrangement of physical components connected or related in such a manner as to command, regulate, direct, or govern itself or another system.

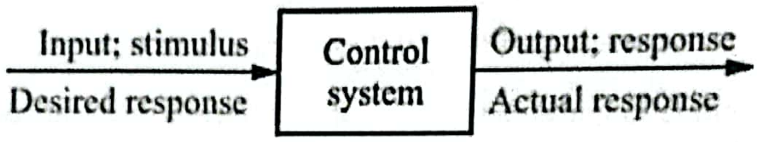
Control Engineering:
Control engineering or Control systems engineering is based on the foundations of feedback theory and linear system analysis, and it integrates the concepts of network theory and communication theory.
It is the engineering discipline that applies control theory to design systems with predictable behaviors. The practice uses sensors to measure the output performance of the device being controlled (often a vehicle) and those measurements can be used to give feedback to the input actuators that can make corrections toward desired performance. When a device is designed to perform without the need for human inputs for correction it is called automatic control (such as cruise control for regulating a car's speed). Multi-disciplinary in nature, control systems engineering activities focus on the implementation of control systems mainly derived by mathematical modeling of systems of a diverse range.

Why is control important (for production process / in the plant)?
(1) Safety: Prevent injury to plant personnel, protect the environment by preventing emission and

Description of a Control system:

A control system is a system capable of *monitoring* and *regulating* the operation of a process or plant. The study of the control system is essentially a study of an important aspect of systems engineering and its applications.

A control system consists of subsystems and processes (or plants) assembled for the purpose of controlling the outputs of the process. For example, a furnace produces heat as a result of the flow of fuel. In this process, the flow of fuel in the ***input***, and heat to be controlled is the ***output***.



There are two common classes of control systems, with many variations and combinations: logic or sequential controls, and feedback or linear controls. There is also fuzzy logic, which attempts to combine some of the design simplicity of logic with the utility of linear control. Some devices or systems are inherently not controllable.

Classification of Control System

Controls are classified with respect to:

- technique involved to perform control (*i.e.* human/machines): **manual/automatic control**
- creation of control system (i.e. natural / manmade): **natural/ manmade /combinational control**
- Time dependence of output variable (*i.e.* constant/changing): **regulator/servo,** (also known as regulating/tracking control)
- Time-type control (Continuous/ discrete): Continuous/Discrete time control
- Linearity of the control system (linear/nonlinear): **Linear/nonlinear control system**
- Parameter distribution (lumped/ distributed)
- Based on the number of input output (SISO, MISO) system
- fundamental structure / configuration of the control (*i.e.* the information used for computing the control): **Open-loop/feedback control,** (also known as open-loop/closed-loop control)

<u>Manual/Automatic Controls - Examples</u>

A system that involves:

- A person controlling a machine is called **manual control.** *<u>Ex</u>: Driving a car*
- A machine only is called an **automatic control**. *<u>Ex</u>: Central AC*

<u>Servo/Regulator Controls – Examples</u>

An *automatic* control system designed to:

- Follow a changing reference is called a **tracking control** or a **servo.** *<u>Ex</u>: Remote control car*
- Maintain an output fixed (regardless of the disturbances present) is called a **regulating control** or a **regulator.** *<u>Ex</u>: Cruise control*

<u>Natural / Manmade / Combinational Control System</u>

The systems inside a human being or a biological system are known as natural control systems. For example, the human eye has a biological (or natural) control system that varies the pupil diameter to maintain constant light intensity to the retina. As the light intensity increases, the optical nerve sends a signal to the brain, which commands internal eye muscles to decrease the pupil's eye diameter.

When the light intensity decreases, the pupil diameter increases.

The various systems that are designed and developed or manufactured by human beings are known as manmade control systems. An automobile system with gears, accelerators, the braking system is a good example of the manmade control system.

The combination of a natural control system and a manmade control system is known as a combinational control system. A driver driving a car is an example of combinational control systems. In such a system, for the successful operation of the system, it is necessary that natural systems of the drive along with systems in vehicles which are manmade must be active.

Continuous-Time and Discrete-Time Control System

If all the system variables of a control system are a function of time, it is termed as a **continuous-time control system**. The speed control of a dc motor with tacho-generator feedback is an example of continuous-time control systems.

If one or more system variables of a control system are known at a certain discrete-time, it is termed as a **discrete-time control system**. The microprocessor or computer-based system is an example of discrete-time control systems.

Linear and Nonlinear Control System

A control system is said to be linear if it satisfies the following properties.

(a) The principle of superposition is applicable to the system. This means the response to several inputs can be obtained by considering one input at a time and then algebraically adding the individual results. Mathematically principle of superposition is expressed by two properties

Additive Property which says that for x and y belonging to the domain of the function f then we have, $f(x+y) = f(x) + f(y)$

Homogeneous Property which says that for any x belonging the domain of the function f and for any scalar constant a, we have, $f(ax) = af(x)$

(b) The differential equation describing the system is linear having its coefficients as constant.

(c) Practically the output *i.e.* response varies linearly with the input *i.e.* forcing function for linear systems.

A control system is said to be nonlinear, if,

(a) It does not satisfy the superposition.

(b) The equations describing the system are nonlinear in nature. The function $f(x) = x^2$ is nonlinear because

$f(x1+x2) = (x1+x2)^2 \neq (x1)^2 + (x2)^2$ and $f(ax) = (ax)^2 \neq a(x)^2$

(c) The output does not vary linearly for nonlinear systems.

Lumped and Distributed-Parameter Control Systems

If a control system can be represented by ordinary differential equations, such as a control system is called a lumped-parameter control system. In the case of electrical networks, parameters such as resistance, inductance, capacitance, etc. are lumped-parameter systems.

If a control system can be described by partial differential equations, such a control system is known as a distributed-parameter control system. In a long transmission line, its parameters such as resistance and inductance are totally distributed along with it. Therefore, long transmission line characteristics are always described by partial differential equations.

Single-Input-Single-Output (SISO) and Multiple-Input-Multiple-Output (MIMO) Control Systems

- If a control system has one input and one output, it is termed as a **single-input-single-output (SISO) control system**.
- If a control system has more than one i

correction to make that output conform to the desired output.

- In **closed-loop control,** the system includes a sensor to measure the output and uses the feedback of the sensed value to influence the control input variable.

Examples of Open-Loop & Feedback Controls

An electric toaster is an open-loop control. *Since*

- The controller is based on knowledge.
- The output is not used in control computation

A water tank of an ordinary flush toilet is a (basic) feedback control *since the* output is fed back to control computation

Advantage of the Control system

We build control systems for four primary reasons

1. Power amplification
2. Remote control
3. The convenience of the input form
4. Compensation of the disturbances

Block Diagram

- It represents the structure of a control system.
- It helps to organize the variables and equations representing the control system.
- It is composed of:
  - boxes, that represents the components of the system including their causality;
  - Lines with arrows that represent the actual dynamic variables, such as *speed*, *pressure*, *velocity*, etc.

System configurations - *open and closed-loop systems*

- ***Open-loop control***: An open-loop control is applied to achieve the desired system response using a controller or an actuator without feedback (fig. 1(a)).

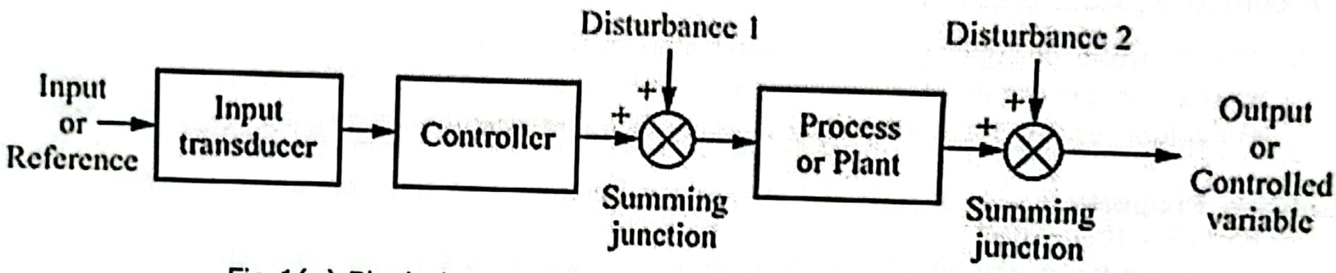


Fig 1(a) Block diagram of an open-loop control system

Features of open-loop control:

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 the desired system accuracy.
2. They are not usually troubled with problems of ***instability***

For example, the plant can be a furnace or air conditioning system, where the output variable is temperature. The controller in a heating system consists of fuel valves and the electrical system that operates the valves.
The distinguishing characteristic of an open-loop control system is that it cannot compensate for any disturbances that add to the controller's driving signal and plant output signal.

Disturbances: Disturbance is a signal which tends to adversely affect the value of the output of a system. Disturbances are two types:

Internal Disturbance: If such a disturbance is generated within the system itself, it is called an internal disturbance.

External Disturbance: The disturbance generated outside the system acting as an extra input to the system in addition to its normal input, affecting the output adversely is called an external disturbance.

For example, if the controller is an electronic amplifier and disturbance 1 as shown in Figure 1.6(a) is noise, then any additive amplifier noise at the first summing junction will also drive the process, corrupting the output with the effect of the noise. The output of an open-loop system is corrupted not only by signals that add to the controller's commands but also by the disturbance at the output. The system cannot correct for these disturbances, either.

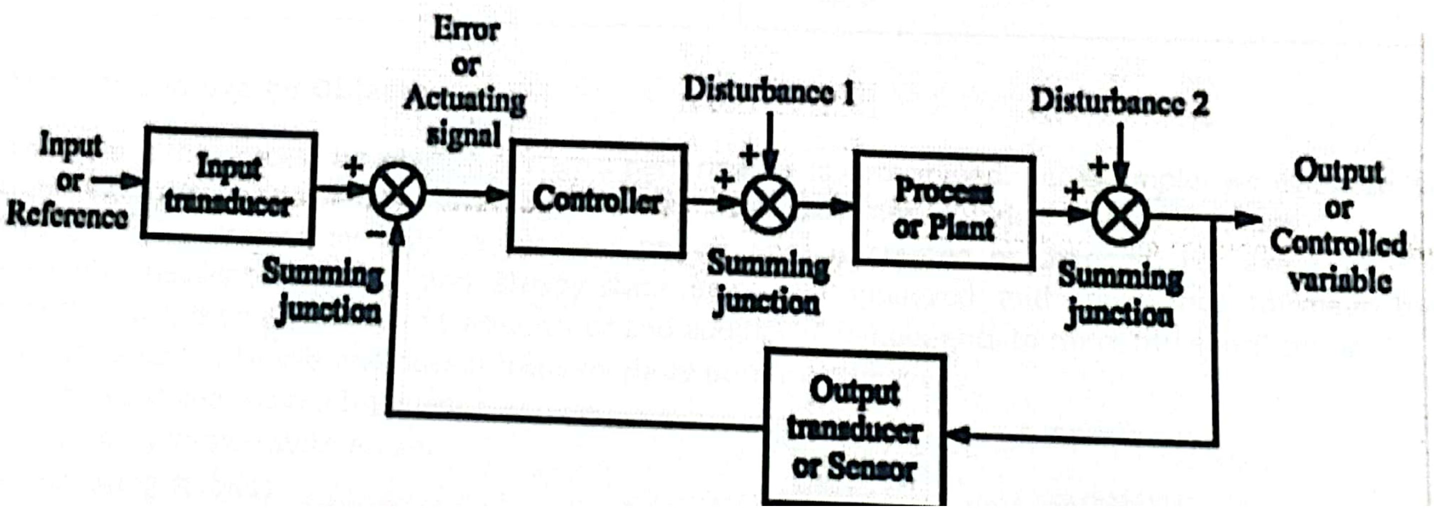
Open-loop systems do not monitor or correct the output for disturbances; however, they are simpler and less expensive than closed-loop systems.

The disadvantages of open-loop systems, namely sensitivity to disturbances and inability to correct for these disturbances, may be overcome by using closed-loop systems.

Advantages of Open-Loop Control System
The followings are the advantages of an open-loop control system:
(a) These systems are simple in construction and design.
(b) These systems are economical.
(c) These systems are easy from a maintenance point of view.
(d) Usually, these systems are not much troubled with problems of stability.
(e) These systems are convenient to use when output is difficult to measure.

Disadvantages of Open-Loop Control System
The followings are the disadvantages of an open-loop control system:
(a) These systems are not accurate and reliable because of their accuracy depends on the accuracy of the calibration.
(b) In these systems, inaccuracy results are obtained with parameter variations *i.e.* internal disturbances.
(c) Recalibration of the controller is required from time to time for maintaining quality and accuracy.

- *__Closed-loop/feedback control__*: A closed-loop control is used to achieve the desired system response using a controller with the output measurement as a feedback signal. The use of feedback enables us to improve system performance at the cost of introducing the measurement noise and stability problem.



The input transducer converts the form of the input to the form used by the controller. An transducer, or sensor, measures the output response and converts it into the form used by controller. [For example, if the controller uses electrical signals to operate the valves of a temperat control system, the input position and the output temperature are converted to electrical signals. Th input position can be converted to a voltage by a potentiometer, a variable resistor, and the output temperature can be converted to a voltage by a thermistor, a device whose electrical resistance changes with temperature.]

The first summing junction algebraically adds the signal from the input to the signal from the output, which arrives via the feedback path, the return path from the output to the summing junction. In Figure 1(b), the output signal is subtracted from the input signal. The result is generally called the actuating signal. However, in systems where both the input and output transducers have unity gain (that is, the transducer amplifies its input by 1), the actuating signal's value is equal to the actual difference between the input and the output. Under this condition, the actuating signal is called the error.

The closed-loop system compensates for disturbances by measuring the output response, feeding that measurement back through a feedback path, and comparing that response to the input at the summing junction. If there is any difference between the two responses, the system drives the plant, via the actuating signal, to make a correction. If there is no difference, the system does not drive the plant, since the plant's response is already the desired response.

Closed-loop systems, then, have the obvious advantage of greater accuracy than open-loop systems. They are less sensitive to noise, disturbances, and changes in the environment. Transient response and steady-state error can be controlled more conveniently and with greater flexibility in closed-loop systems, often by a simple adjustment of gain (amplification) in the loop and sometimes by redesigning the controller. We refer to the redesign as compensating the system and to the resulting hardware as a compensator. On the other hand, closed-loop systems are more complex and expensive than open-loop systems.

Closed-loop systems monitor the output and compare it to the input. If an error is detected, the system corrects the output and hence corrects the effects of disturbances.

Advantages of Closed-Loop Control System

The followings are the advantages of a closed-loop control system:

(a) In these systems, accuracy is very high due to the correction of any arising error.

(b) Since these systems sense environmental changes as well as internal disturbances, the errors are modified.

(c) There is a reduced effect of nonlinearity in these systems.

(d) Systems have high bandwidth i.e. high operating frequency zone.

(e) There are facilities for automation in these systems.

Disadvantages of Closed-Loop Control System

The followings are the disadvantages of a closed-loop control system:

(a) Systems are complicated in design and, hence, costlier.

(b) Systems may be unstable.

Comparison of open-loop and closed-loop systems

Open Loop	Closed Loop
Any change in output has no effect on the input i.e. feedback does not exist.	Changes in output affect the input which is possible by the use of feedback.
Output measurement is not required for the operation of the system.	Output measurement is necessary.
Feedback element is absent.	Feedback element is present.
The error detector is absent.	The error detector is necessary.
It is inaccurate and unreliable.	Highly accurate and reliable.
Highly sensitive to the disturbances.	Less sensitive to the disturbances.
Highly sensitive to environmental changes.	Less sensitive to environmental changes.
Bandwidth is small.	Bandwidth is large.
Simple to construct and cheap.	Complicated to design and hence costly.
Generally stable in nature.	Stability is a major consideration while designing.
Highly affected by nonlinearities.	Reduced effect of nonlinearities.

Computer Controlled Systems

In modern systems, the controller (or compensator) is a digital computer. The advantage of using a computer is that many loops can be controlled or compensated by the same computer through time-sharing. Furthermore, any adjustments of the compensator parameters required to yield the desired response can be made by changes in software rather than hardware.

Analysis and Design objectives of a control system

Let's define our analysis and design objectives

1.) **Transient Response :** We analyze the system for its existing transient response. We then adjust parameters or design components to yield a desired transient response. (this is our first analysis and design objective)

2.) **Steady-State Response :** We are concerned about the accuracy of steady-state response. We analyze system's steady-state error, and then design corrective action to reduce steady-state error. (this is our second analysis and design objective)

3.) **Stability :** Discussion of transient response and steady state error is moot if the system does not have *stability*! For a linear sytem, we can write;

Total response = Natural response + Forced response

For a control systems to be useful, the natural response must eventually approach to zero, thus leaving only the forced response. If the natural response approaches to zero, we can say the system is "stable"

Analysis and Design Objectives

Analysis is the process by which a system's performance is determined. For example, we evaluate its transient response and steady-state error to determine if they meet the desired specifications.
Design is the process by which a system's performance is created or changed. For example, if a system's transient response and steady-state error are analyzed and found not to meet the specifications, then we change parameters or add additional components to meet the specifications.
Control systems analysis and design focus on three primary objectives:
(1) Producing the desired transient response
(2) Reducing steady-state errors
(3) Achieving stability

Step 3 Represent the physical system as a schematic.
Step 4 Use the schematic to obtain a mathematical model, such as a block diagram.
Step 5 Reduce the block diagram.
Step 6 Analyze and design the system to meet specified requirements and specifications that inc
stability, transient response, and steady-state performance.

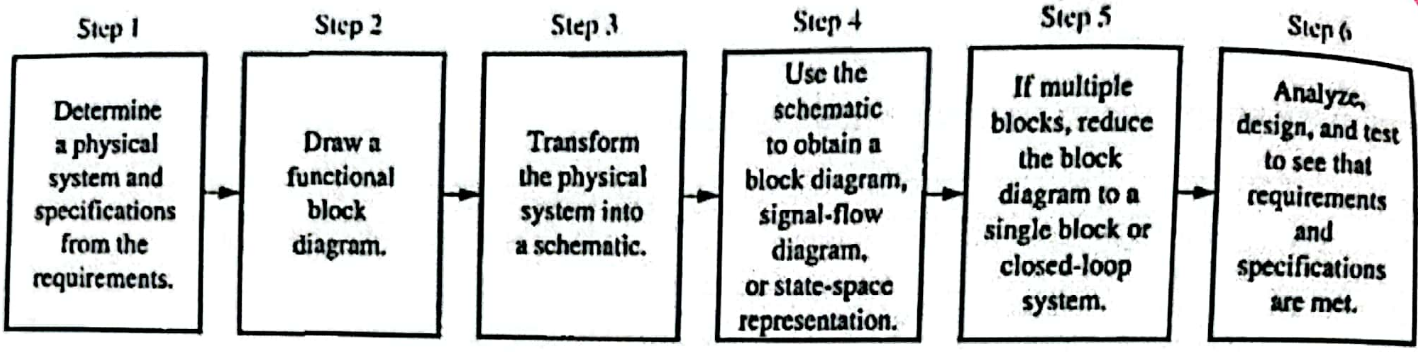


Fig. 1.11 the control system design process

Figure 1.11 is feedback and communication during each phase. For example, if testing (Step 6) shows that requirements have not been met, the system must be redesigned and retested. Sometimes requirements are conflicting and the design cannot be attained. In these cases, the requirements have to be re-specified and the design process repeated. Let us now elaborate on each block of Figure 1.11.

Step 1: Transform Requirements into a Physical System
We begin by transforming the requirements into a physical system. Using the requirements, design specifications, such as desired transient response and steady-state accuracy, are determined.

Step 2: Draw a Functional Block Diagram
The designer now translates a qualitative description of the system into a functional block diagram that describes the component parts of the system (that is, function and/or hardware) and shows their interconnection.

Step 3: Create a Schematic
As we have seen, position control systems consist of electrical, mechanical, and electromechanical components. After producing the description of a physical system, the control systems engineer transforms the physical system into a schematic diagram. The control system designer can begin with the physical description to derive a schematic.

Step 4: Develop a Mathematical Model (Block Diagram)
Once the schematic is drawn, the designer uses physical laws, such as Kirchhoff's laws for electrical networks and Newton's law for mechanical systems, along with simplifying assumptions, to model the system mathematically. These laws are
Kirchhoff's voltage law: The sum of voltages around a closed path equals zero.
Kirchhoff's current law: The sum of electric currents flowing from a node equals zero.
Newton's laws: The sum of forces on a body equals zero; the sum of moments on a body equals zero.

Kirchhoff's and Newton's laws lead to mathematical models that describe the relationship between the input and output of dynamic systems. One such model is the linear, time-invariant differential equation, Eq. (1.2):

$$\frac{d^m c(t)}{dt^n} + d_{n-1}\frac{d^{m-1} c(t)}{dt^{n-1}} + \cdots + d_0 c(t) = b_m \frac{d^m r(t)}{dt^m} + b_{m-1}\frac{d^{m-1} r(t)}{dt^{m-1}} + \cdots + b_0 r(t) \tag{1.12}$$

Many systems can be approximately described by this equation, which relates the output, c(t), to the input, r(t), by way of the system parameters, ai, and bj.

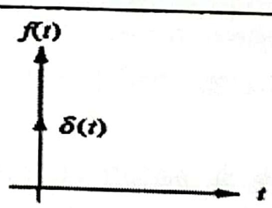
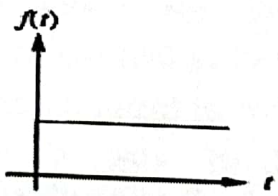
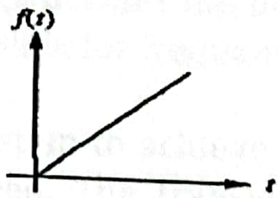
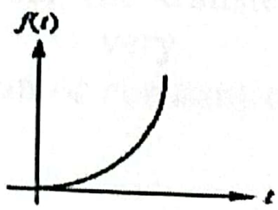
In addition to the differential equation, the *transfer function* is another way of mathematically modeling a system. The model is derived from the linear, time-invariant differential equation using what we call the *Laplace to transform*. Although the transfer function can be used only for linear systems, it yields more intuitive information than the differential equation. We will be able to change system parameters and rapidly sense the effect of these changes on the system response. The transfer function is also useful in modeling the interconnection of subsystems by forming a block diagram.

Still another model is the *state-space representation.* One advantage of state-space methods is that they can also be used for systems that cannot be described by linear differential equations. Further, state-space methods are used to model systems for simulation on the digital computer. Basically, this representation turns an nth-order differential equation into *n* simultaneous first-order differential equations.

Step 5: Reduce the Block Diagram
Subsystem models are interconnected to form block diagrams of larger systems, where each block has a mathematical description.
In order to evaluate system response, we need to reduce this large system's block diagram to a single block with a mathematical description that represents the system from its input to its output. Once the block diagram is reduced, we are ready to analyze and design the system.

Step 6: Analyze and Design
The next phase of the process, following block diagram reduction, is analysis and design. Test input signals are used, both analytically and during testing, to verify the design. These inputs are impulses, steps, ramps, parabolas, and sinusoids, as shown in Table 1.1.

TABLE 1.1 Test waveforms used in control systems

Input	Function	Description	Sketch	Use
Impulse	$\delta(t)$	$\delta(t) = \infty$ for $0- < t < 0+$ $= 0$ elsewhere $\int_{0-}^{0+} \delta(t)dt = 1$		Transient response Modeling
Step	$u(t)$	$u(t) = 1$ for $t > 0$ $= 0$ for $t < 0$		Transient response Steady-state error
Ramp	$tu(t)$	$tu(t) = t$ for $t \geq 0$ $= 0$ elsewhere		Steady-state error
Parabola	$\frac{1}{2}t^2u(t)$	$\frac{1}{2}t^2u(t) = \frac{1}{2}t^2$ for $t \geq 0$ $= 0$ elsewhere		Steady-state error
Sinusoid	$\sin \omega t$			Transient response Modeling Steady-state error

BEE501- CONTROL SYSTEM

UNIT 1

SYSTEMS AND THEIR REPRESENTATION

Definition of Control System

A control system is a system of devices or set of devices, that manages commands, directs or regulates the behavior of other device(s) or system(s) to achieve desire results. In other words the **definition of control system** can be rewritten as **A control system is a system, which controls other system.** As the human civilization is being modernized day by day the demand of automation is increasing accordingly. Automation highly requires control of devices.

Requirement of Good Control System

Accuracy: Accuracy is the measurement tolerance of the instrument and defines the limits of the errors made when the instrument is used in normal operating conditions. Accuracy can be improved by using feedback elements. To increase accuracy of any control system error detector should be present in control system.

Sensitivity : The parameters of control system are always changing with change in surrounding conditions, internal disturbance or any other parameters. This change can be expressed in terms of sensitivity. Any control system should be insensitive to such parameters but sensitive to input signals only.

Noise : An undesired input signal is known as noise. A good control system should be able to reduce the noise effect for better performance.

Stability : It is an important characteristic of control system. For the bounded input signal, the output must be bounded and if input is zero then output must be zero then such a control system is said to be stable system.

Bandwidth : An operating frequency range decides the bandwidth of control system. Bandwidth should be large as possible for frequency response of good controlsystem.

Speed : It is the time taken by control system to achieve its stable output. A good control system possesses high speed. The transient period for such system is very small.

Oscillation : A small numbers of oscillation or constant oscillation of output tend to system to be stable.