→: Unit-6 :←

10.5 Dynamic Models and Analogies

Often, analytical models are used for the design, development, modification and control of a mechatronics system. A model of component is an idealization of those component properties in the form of system equations. These are the equations representing the relationship between the input and the output of a component. A mechatronics system consists of many components such as mechanical, electrical, fluid and thermal systems. This section explains the basic concepts associated with the study of mechatronics systems with models. Further, how analytical component models can be integrated to obtain the overall model of the system is discussed. The analytical models are needed to understand the behavior of a system.

Mechanical Systems

Mechanical systems are categorized into two groups on the basis of the types of motion:

1. translational mechanical systems;
2. rotational mechanical systems.

The basic forms of the mechanical system building blocks are springs, damper dashpots and masses. Springs represent the stiffness of a system, dashpots represent the forces opposing the motion and masses represent the inertia or resistance to acceleration, Newton's second law of motion can be applied to any mechanical system for modeling.

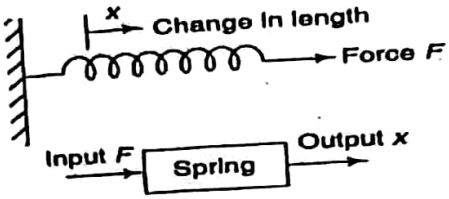


Figure 10.23 | Spring.

1. **Spring:** The force required to stretch a spring (Figure 10.23) to a distance "x" is given by

$$F = Kx$$

where K is a constant known as spring stiffness (N/m) and x the displacement. For torsional spring, $T = K\theta$, where T is the torque and θ the angular displacement.

2. **Damper:** A damper is a mechanical component that provides viscous friction or damping in the motion control. It consists of a piston and an oil-filled cylinder. A force is experienced when there is relative motion between the piston rods. The dashpot simply absorbs energy. The force developed by a viscous damper shown in Figure 10.24 is directly proportional to the velocity; therefore

$$F \propto v$$

$$F = Bv = B\frac{dx}{dt}$$

where B is a constant known as *damping coefficient*.

3. **Mass:** The mass of a body is the quantity of matter in it. If a force (F) is applied to a mass M, the motion of the mass is given by

$$F = Ma$$

where a is the acceleration of the mass (Figure 10.25). Also

$$F = \frac{dv}{dt} \text{ or } M\frac{d^2x}{dt^2}$$

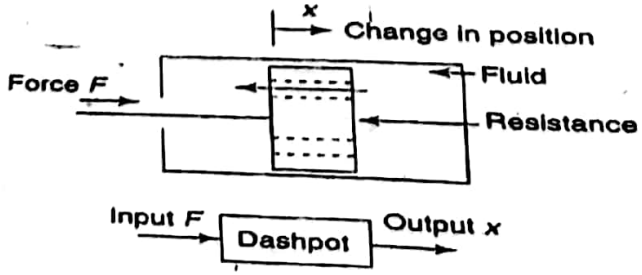


Figure 10.24 | Dashpot.

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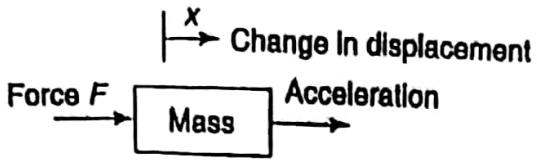


Figure 10.25 | Mass.

For the torsional system

$$T = J\frac{d^2\theta}{dt^2}$$

Translational Mechanical System

Spring mass damper system A spring mass damper system is shown in Figure 10.26. The system is fixed at one end, and the mass is supported by a spring and damper. The mass is excited by force and is free to oscillate. The equation of motion relating the horizontal motion "x" of mass to applied force can be developed with the help of a free body diagram shown in Figure 10.27.

Note that in this case

$$\text{Spring force} = \text{stiffness} \times \text{displacement}$$

$$\text{Inertia force} = \text{mass} \times \text{acceleration}$$

$$\text{Damping force} = \text{damping coefficient} \times \text{velocity}$$

From free body diagram, sum of forces acting on mass M is

$$M = f(t) - Kx - Bv$$

$$= f(t) - Kx - B\frac{dx}{dt} \qquad (10.5)$$

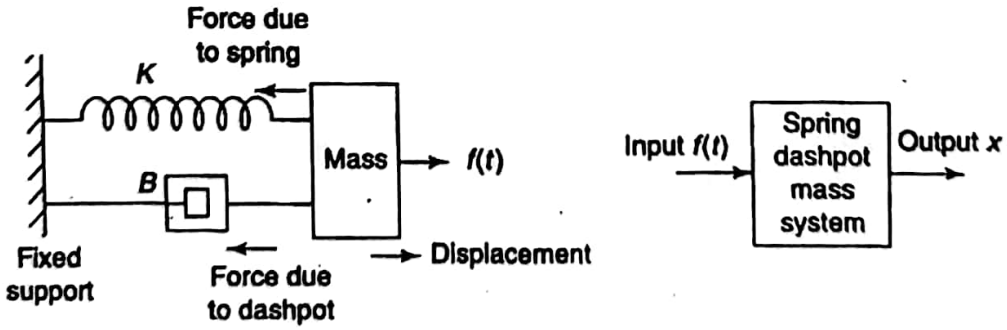


Figure 10.26 | Simple spring mass damper system.

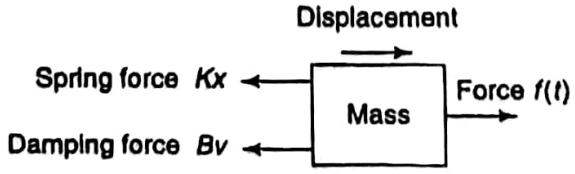


Figure 10.27 | Free body diagram.

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Also

$$\text{Net force applied to mass (inertia force)} = \text{mass} \times \text{acceleration} = M\frac{d^2x}{dt^2} \tag{10.6}$$

Applying Newton's second law of motion and combining Eqs. (10.6) and (10.7), we get

$$M\frac{d^2x}{dt^2} = f(t) - Kx - B\frac{dx}{dt}$$

$$M\frac{d^2x}{dt^2} + B\frac{dx}{dt} + Kx = f(t) \tag{10.7}$$

Equation (10.7) is called the *differential equation* that describes the relationship between input and output. Taking Laplace transform of Eq. (10.7), we have

$$Ms^2X(s) + BsX(s) + KX(s) = F(s)$$

The transfer function of the system can therefore be written as

$$\frac{X(s)}{F(s)} = \frac{1}{Ms^2 + Bs + K}$$

Rotational Mechanical Systems

The rotational mechanical systems are similar to translational mechanical systems. Here, torque replaces force and displacement replaces translational displacement. The rotational mechanical system essentially consists of three main components:

1. **Torsional spring (Figure 10.39):** When a torque T is applied to the free end of the spring, it causes the spring to twist with an angular displacement θ. The torque T is given by

$$T = K_t\theta$$

where K_t is the torsional spring stiffness (N m/rad).

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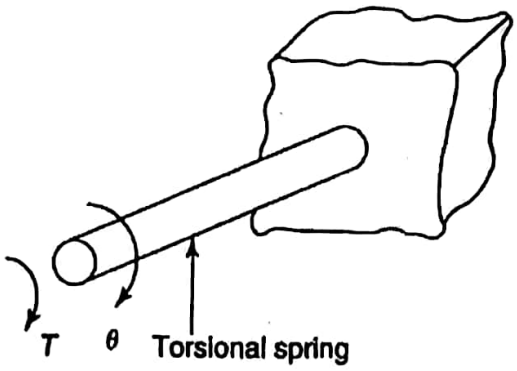


Figure 10.39 | Torsional spring.

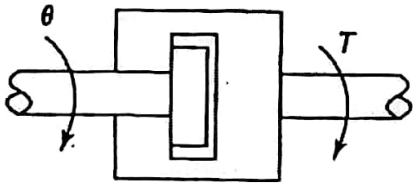


Figure 10.40 | Torsional damper.

2. **Torsional damper:** Torsional damper is similar to viscous damper (see Figure 10.40). The torque required to rotate a damper with an angular velocity ω is given by $T = B\omega$, where B is damping coefficient and ω the angular velocity, given by $d\theta/dt$. Therefore

$$T = B\frac{d\theta}{dt}$$

3. **Mass:** The amount of torque in a rotating body to obtain required acceleration depends on mass and its distribution about the center of rotation. This is described by a moment of inertia. If rotor with moment of inertia "J" is accelerated by torque T, then the torque is given by

$$T = J\alpha$$

where α is the angular acceleration. Therefore,

$$T = J\frac{d^2\theta}{dt^2}$$

This is nothing but Newton's second law of motion.

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Geared System

Geared system provides a mechanical advantage to the rotational systems. For simple system of gears shown in Figure 10.48, the relation among torque, angle and number teeth is given by

$$\frac{T_2}{T_1} = \frac{\theta_1}{\theta_2} = \frac{Z_2}{Z_1} = \frac{N_1}{N_2}$$

Consider a simple geared system shown in Figure 10.49.

The equation of motion can be written as

$$[Js^2 + Bs + K]\theta_2(s) = T_1(s)\frac{N_1}{N_2}$$

Here $\theta_2(s) = n\theta_1(s)$ and $N_2/N_1 = n$. Substituting in the above equation, we get

$$[Js^2 + Bs + K]n^2\theta_1(s) = T_1(s)$$

The mechanical impedance is multiplied by n^2, for example, $J_e = Jn^2$. Therefore

$$[J_e s^2 + B_e s + K_e]\theta_1(s) = T_1(s)$$

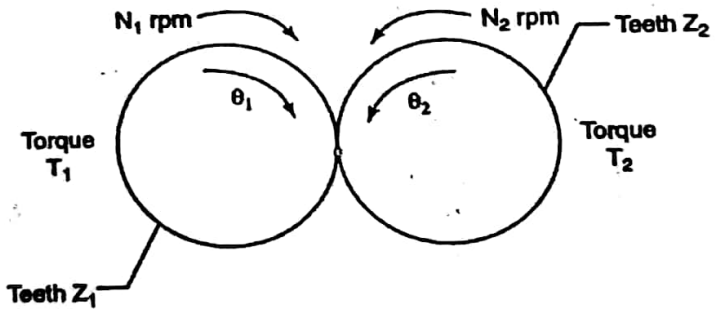


Figure 10.48 | Simple geared system.

Electrical Systems

In this section, we will apply the transfer function to the electrical circuits comprising passive elements. Basically, we will deal with the following passive elements: inductors, capacitors and resistors. Table 10.2 gives the components and the relationships between voltage and current.

Electrical networks can be analyzed using Kirchhoff's current and voltage laws:

1. Kirchhoff's current law states that the sum of the currents flowing into a junction equals the sum of the current flowing out of a junction.
2. Kirchhoff's voltage law states that the sum of the voltage input equals the sum of the voltage drop in any closed loop.

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Electromechanical Systems

There are many electromechanical systems such as potentiometers, motors and generators. A very important electromechanical device is a DC motor that essentially converts an electrical input signal into a mechanical output signal. The motor basically consists of a coil (stator) and an armature coil which is free to rotate. The stator coil is located in the magnetic field provided by a current that passes through the coils. When current flows through an armature coil, the interaction between fields of armature and the stator causes the motor to turn. In the armature-controlled DC motor, the speed of the motor is varied by varying the voltage on the armature circuit, and voltage supply to the field winding is kept constant.

Thermal and Fluid Systems

Thermal systems are concerned with the transfer of heat from one body to another, and these systems are governed by the laws of thermodynamics and heat transfer. Fluid systems, on the other hand, contain tanks and reservoirs connected through pipes, fittings, valves and flow-measuring elements. We define two dynamic components here:

1. **Resistance**
   - **Thermal resistance:** This is the change in temperature for a unit change in heat flow rate and is given by

$$\text{Thermal resistance} = \frac{\text{Change in temperature}}{\text{Heat flow rate}}$$

$$R = \frac{\Delta T}{Q}$$

   - **Fluid resistance:** This is the change in pressure for a unit change in flow rate,

$$\text{Flow resistance, } R = \frac{\Delta P}{Q} = \frac{h}{Q}$$

2. **Capacitance**
   - **Thermal capacitance:** This is the measure of an object to store heat, and is related to the rise in temperature with heat transfer,

$$C = Q/\frac{dT}{dt}$$

     where dT/dt is the rate of change in temperature and Q the heat transfer rate.
   - **Fluid capacitance:** It relates the pressure head "h" developed and the net tank inflow rate Q. Fluid capacitance is given by

$$C = \frac{Q}{dh/dt} = \frac{A}{\rho g}$$

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Hydraulic Power System

A hydraulic power system converts the hydraulic pressure into translational or rotational motion. Figure 10.72 shows a hydraulic system in which an input displacement "x" of spool valve is translated into an output displacement "y" of the piston rod.

The movement of spool valve to the right side by "x" enables the hydraulic pressure supply to result a flow of fluid into the left-hand side of the cylinder. Thereby, a piston rod moves to the right-hand side. The return oil at the right-hand side of the piston is expelled through the return port.

The rate of flow of fluid is essentially proportional to input motion of the spool valve:

$$Q = K_v x \tag{10.94}$$

where K_v is the valve constant. The flow rate in the cylinder is given by

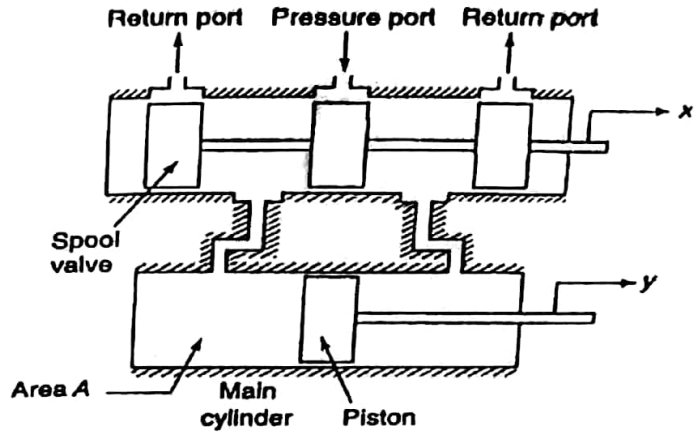


Figure 10.72 | Hydraulic power system.

$$Q = A\frac{dy}{dt} \tag{10.95}$$

where A is the cross-sectional area of cylinder.

Combining Eqs. (10.94) and (10.95) gives the differential equation of a hydraulic system:

$$A\frac{dy}{dt} = K_v x$$

The above system can be converted into a feedback device with the modification shown in Figure 10.73, known as the *hydraulic servo mechanism.*

Hydraulic servo mechanism is a feedback device to control the piston movement. The opening of a valve through which the oil enters is set up due to the relative motion between the spool valves of the sliding sleeve.

The discharge of oil through the pressure port is given by

$$Q = K_v(x - z) \tag{10.96}$$

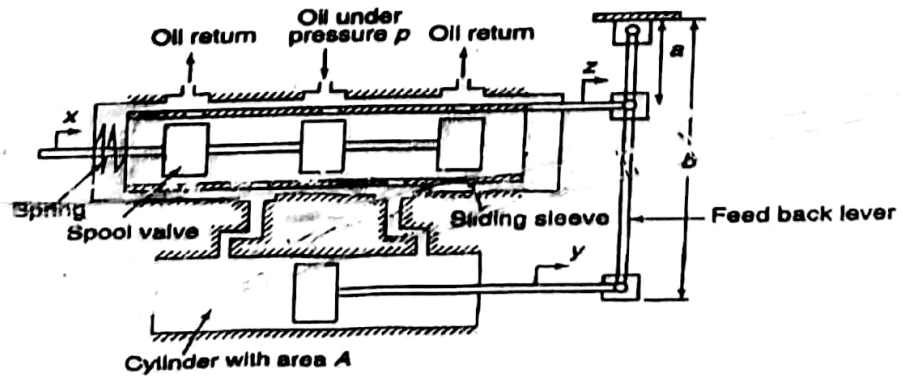


Figure 10.73 | Hydraulic servo mechanism.

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where K_v is the valve constant. The discharge in the cylinder is given by

$$Q = A\frac{dy}{dt} \tag{10.97}$$

where A is the cross-sectional area of the cylinder.

Combining Eqs. (10.96) and (10.97)

$$A\frac{dy}{dt} = K_v(x - z) \tag{10.98}$$

From the feedback lever geometry

$$\frac{z}{y} = \frac{a}{b}$$

$$z = \frac{a}{b}y \tag{10.99}$$

Substituting Eq. (10.99) in Eq. (10.98) we get

$$A\frac{dy}{dt} = K_v\left(x - \frac{a}{b}y\right)$$

$$A\frac{dy}{dt} + K_v\frac{a}{b}y = K_v x$$

This is the differential equation of a hydraulic servo mechanism.

Pneumatic System

A simple pneumatic system consisting of bellows is shown in Figure 10.75. A pneumatic system supplies air to the pressure vessel through a pipe line, and resistance to flow is provided by a constriction.

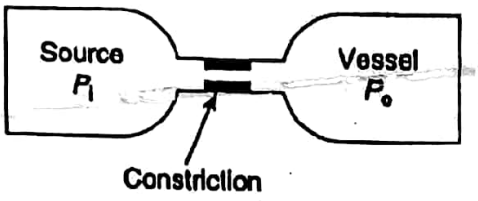


Figure 10.75 | Pneumatic system.

Let P_i be the air pressure of the source, P_o the air pressure in the vessel and C the pneumatic capacitance. Taking mass balance

Rate of gas storage in vessel = Rate of gas flow

$$C\frac{dP_o}{dt} = \frac{P_i - P_o}{R}$$

$$RC\frac{dP_o}{dt} + P_o = P_i$$

This is the differential equation for a simple pneumatic system.

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11 System Response

Learning Objectives

After completing this chapter, you will be able to:

- Find time response from the transfer function for a given input signal.
- Describe the transient response of first- or second-order systems.
- Determine the stability of a system represented as a transfer function using Routh–Hurwitz criterion.
- Find the steady-state error for a unity and non-unity feedback systems.
- Define frequency response and plot frequency response using Nyquist and Bode plots, and analyze them for stability.

In this chapter, we discuss the ideas of modeling of physical system characteristics, such as steady-state errors, transient response characteristics, etc. Further, we introduce the common time domain specifications such as overshoot, settling time, time to rise, etc. We will develop relationships between performance specifications and natural frequency and damping ratio for the second-order system. The issue of ensuring the stability of a control system is important to control system design. The Routh–Hurwitz method is introduced as a useful tool for assessing system stability. Bode plots, Polar plots, etc. are the most powerful tools for analyzing and designing control system in frequency domain. Thus, we will be investigating response and stability of the system to a sinusoidal input as the frequency varies.

11.1 Static Response

The static response of a system is the steady-state error that a system may exhibit between the controlled variable and the input. Whenever a system is disturbed, or whenever an input is applied to a system, the system will be in disturbed state (transient state) for some time, and later on, it gets stabilized or attains a steady-state condition.

The difference between the steady-state value and the input value is known as the steady-state error. It is a measure of the accuracy of a control system.

Steady-State Error for an Open-Loop Control System

From the above definition of steady-state error, the error $E(s)$ for an open-loop control system shown in Figure 11.1 is given by

$$E(s) = R(s) - C(s) \tag{11.1}$$

Also

$$\frac{C(s)}{R(s)} = G(s)$$

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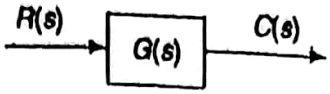


Figure 11.1 | Open-loop system.

$$C(s) = G(s)R(s) \tag{11.2}$$

Substituting Eq. (11.2) in Eq. (11.1) we get

$$E(s) = R(s) - G(s)R(s)$$

$$= [1 - G(s)]R(s)$$

From final value theorem, steady-state error is given as

$$e_{ss} = e(t) = \lim_{s \to 0} sE(s)$$

Therefore

$$e_{ss} = \lim_{s \to 0} s[1 - G(s)]R(s)$$

Steady-State Error of a Closed-Loop Control System with Unity Feedback

A unit feedback system is shown in Figure 11.2. Here, $H(s) = 1$ and transfer function of the systems is

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1 + G(s)} \tag{11.3}$$

We know that

$$\frac{C(s)}{E(s)} = G(s) \tag{11.4}$$

$$E(s) = \frac{C(s)}{G(s)} \tag{11.5}$$

From Eq. (11.3)

$$C(s) = \frac{G(s)R(s)}{1 + G(s)} \tag{11.6}$$

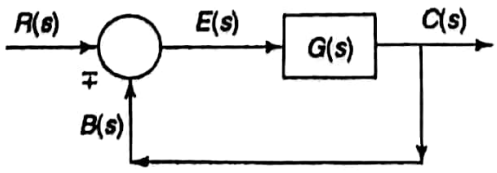


Figure 11.2 | Closed-loop system with unity feedback.

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11.3 Time Response

To fully describe the dynamic behavior of a system, the model developed must describe the relationship between inputs and outputs that are the functions of time. One type of model that is often used to describe the behavior of a control system is a differential equation. Analysis of the system can be done by studying the system differential equation with different inputs. Hence, the dynamic response of a control system is essentially depending on the type of input signal given to analyze the system.

Test Signal

A test signal $r(t)$ is applied to the system (Figure 11.17). This results in a response $c(t)$. Note that both input and output are functions that vary with time. The input signal to systems can take many forms. The common input signals are:

1. **Step input signal:** The step signal is a signal that has zero value that changes to a constant value at a certain point in time (Figure 11.18). A step signal is given by

$$r(t) = \begin{cases} X, & \text{for } t > 0 \\ 0, & \text{for } t < 0 \end{cases}$$

2. **Ramp input signal:** In this case, the reference input variable is considered to have a constant change with respect to time as shown in Figure 11.19. Mathematically, a ramp function is represented by

$$r(t) = \begin{cases} Xt, & \text{for } t > 0 \\ 0, & \text{for } t < 0 \end{cases}$$

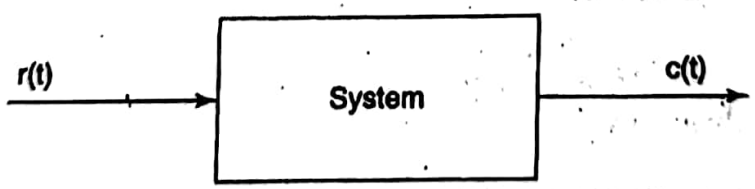
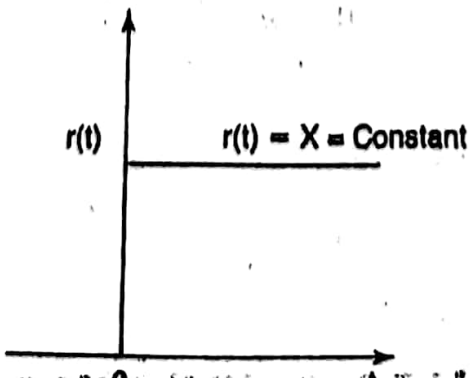


Figure 11.17 System with input and output.



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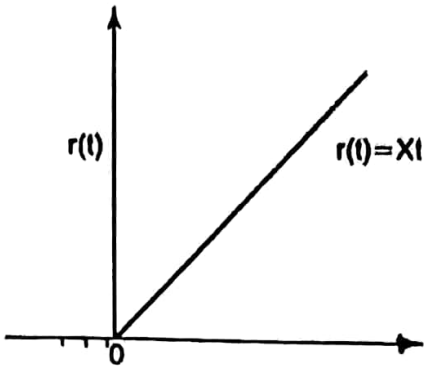


Figure 11.19 | Ramp Input.

3. **Sinusoidal input signal:** A sinusoidal input is one whose oscillations can be described by an equation of the form sin ωt (Figure 11.20). A sinusoidal signal is given by

$$r(t) = A \sin(\omega t + \varphi)$$

4. **Impulse input signal:** An impulse is a very short duration input (Figure 11.21) and can mathematically be represented by

$$r(t) = \partial(t) = \lim_{b \to 0} p(t)$$

Step Response of a First-Order System

Differential equations are the equations involving derivatives. They can be classed as first-order, second-order, third-order, etc. For a first-order equation, the highest order will be dx/dt; for a second-order equation, d^2x/dt^2; etc.

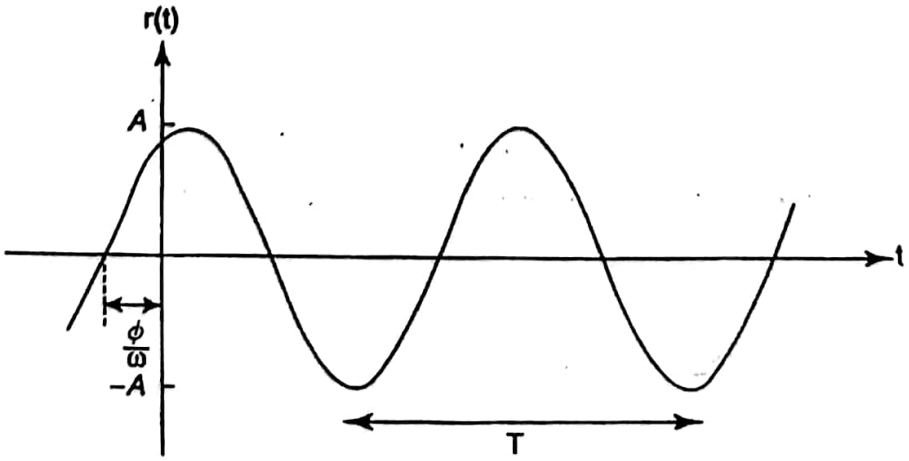


Figure 11.20 | Sinusoidal signal.

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Experimental Determination of the Frequency Responses

The experimental method is used for two purposes:

1. for testing a control system and verification of the control system model;
2. for extracting a mathematical model if the system transfer function is not known.

A typical setup for the experimental determination of frequency response is shown in Figure 11.39. The system requires the following elements:

1. function generator;
2. power supply;
3. dual trace oscilloscope;
4. system under test.

In order to prepare for the test, we need to establish the test frequency range and the input signal amplitude. For a mechanical system, mechanical cycle generators are used to produce sinusoids. Initially, the sinusoidal signal with the lowest frequency is applied; the amplitude and the phase difference between the input and the output are obtained once the transients have settled down. The gain is determined from the above data. The input signal frequency is increased, and output amplitude and phase shift are recorded after the output has settled down and the process is repeated until the entire frequency range.

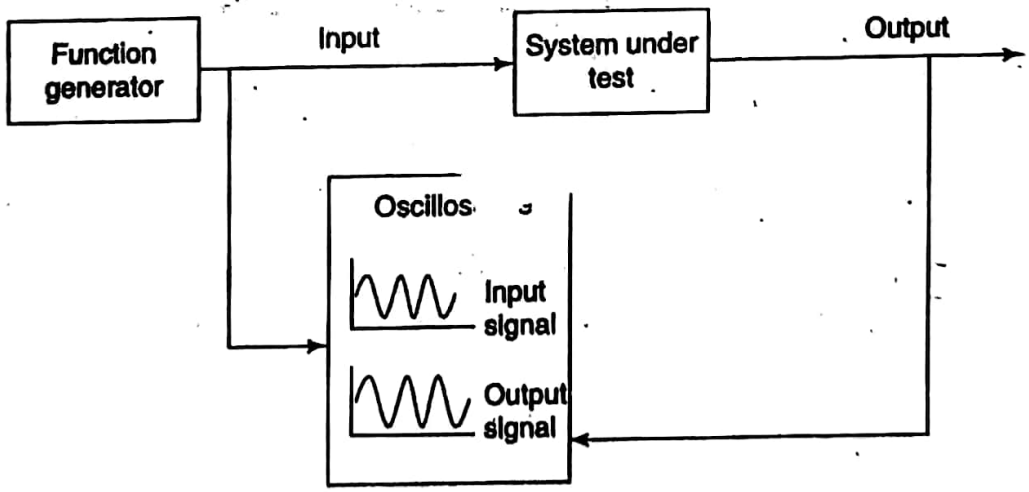


Figure 11.39 | Experimental setup.

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Polar Plots (Nyquist Diagrams)

A polar plot is the loci of vectors drawn for a frequency range. The frequency response is represented by polar coordinates. This is magnitude vs. phase angle plot in the polar coordinate where frequency is varied from zero to infinity.

Procedure to draw polar plots (Nyquist diagram) is as follows:

1. Obtain the transfer function of the system.
2. Replace all s in the transfer function by $j\omega$.
3. Express $M(j\omega)$ in its magnitude form and phase angle.
4. Vary the value of ω from 0 to ∞.
5. Plot the magnitude and phase angle in the polar coordinate.

Let us consider a first-order system shown in Figure 11.40.

Assuming $RC = 0.1$, the transfer function is given by

Replacing s by $j\omega$

$$M(j\omega) = \frac{Y(s)}{X(s)} = \frac{1}{0.1s+1}$$

$$M(j\omega) = \frac{1}{0.1j\omega+1}$$

$$\text{Magnitude, } M = \frac{|1|}{|0.1j\omega+1|} = \frac{1}{\sqrt{1+(0.1\omega)^2}} = \frac{1}{\sqrt{1+0.01\omega^2}}$$

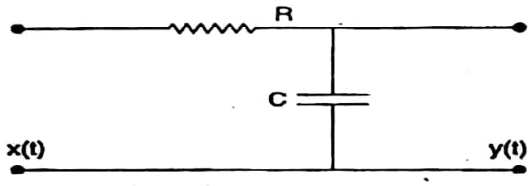


Figure 11.40 | First-order system.

12.10 Digital Controllers

Microprocessor-based digital controllers are very common and have revolutionized the entire measurement and control industry. The power of a digital controller provides advanced features such as adaptive self-tuning, multivariable control and expert systems. Digital controllers used for closed-loop control can generally implement the PI, PD or PID control mode. A digital controller differs from its analog controller mainly with respect to the fact that a digital controller cannot be directly interfaced to feedback transducers or SP potentiometers.

Therefore, an analog-to-digital converter (ADC) is needed for accepting an analog input signal. Further, a digital-to-analog converter (DAC) is needed for interfacing to final control elements. Figure 12.38 shows a closed-loop control system with a digital controller.

Note that the conventional analog controller has been replaced with computer software executing the control algorithm. The summation block is used to produce the error signal. The error signal is the difference of SPs and MVs. The digital controller accepts the analog error signal and digitizes the error signal using the ADC. The digital controller processes this signal according to the control algorithm and produces an appropriate output through DAC. It is also possible for a digital controller to accept the values of SP and MV without a summation block.

The flowchart shown in Figure 12.39 describes steps a digital controller must go through to execute a control algorithm suitable for the closed-loop system in a cycle of events. They are:

1. The digital controller reads the output from ADC to SP input and MV.
2. The present value of error is determined.

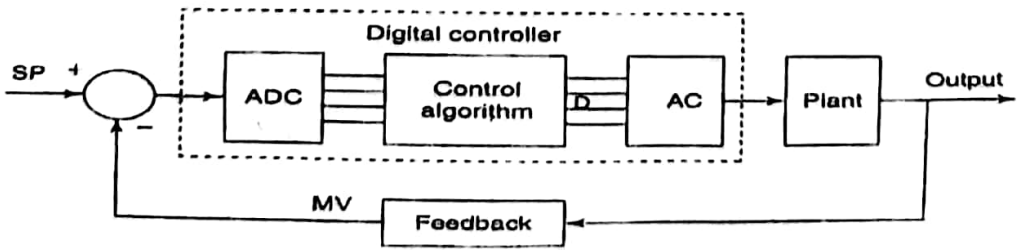


Figure 12.38 | Digital controller.

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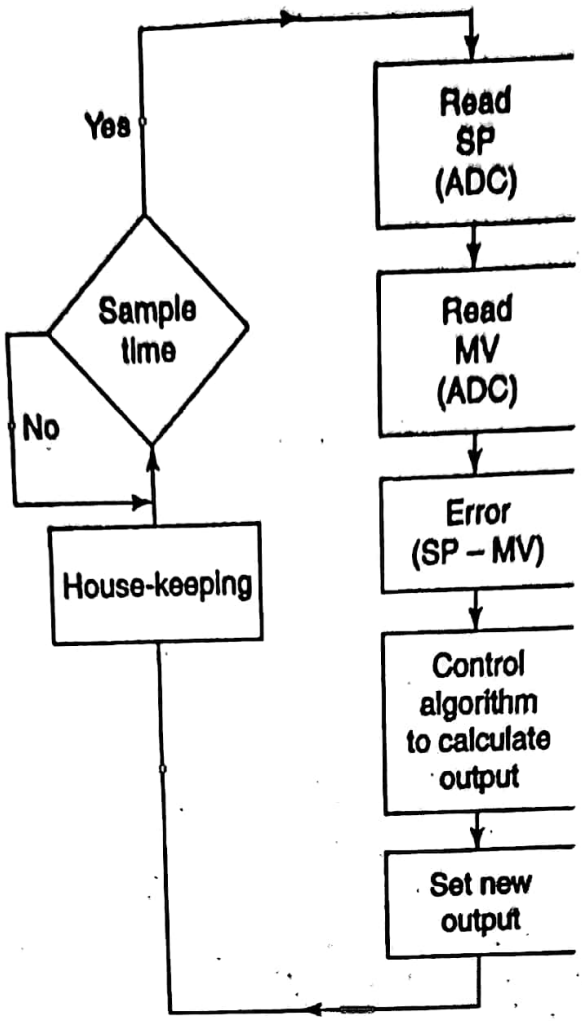


Figure 12.39 | Flowchart for digital controller.

3. A new controller output value is generated based on control algorithm and calculation.
4. The output signal is sent to DAC.
5. Perform house-keeping tasks: A microprocessor/PC will be required to respond to keyboard input and update graphic displays and network communication. These tasks are labeled as house-keeping tasks.
6. Sample time: It is the time interval with which the digital controller will repeat a task. The decision block representing the sample time in the flowchart ensures that the control loop is repeated only at every sampling time interval.

Software is the center of control operation as error must be determined and the controller mode equations solved to determine the necessary output to the final control element (e.g., MOSFETs). There are three tasks for the software to perform:

1. system initialization;
2. loop execution;
3. house-keeping.

Implementation of Control Mode

Proportional Control Algorithm

For analog and digital control it is given by

$$V_c = K_c e \quad \text{(analog)}$$

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Features of Digital Controller

Digital controllers have many advantages over analog controllers. They are:

1. Control mode can be changed by simply changing the control algorithm.
2. No change in hardware is required for changing the control mode action.
3. They provide advanced features such as adaptive self-tuning, multivariable control and expert system.
4. Endless control schemes can be obtained to suit practically any type of system, whereas separate controllers are required for each scheme with analog controllers.
5. They give better accuracy and do not suffer from drift due to temperature effect.

12.11 Adaptive Controllers

The adaptive controllers change the controller's parameter to adapt to the changes and fit the prevailing circumstances. Often control parameter of the process changes with time or load. This will alter the transfer function of the system. Therefore, retuning of the system is desirable for the controllers. For example, a change in the product flow rate in the temperature control system as shown in Figure 12.43 will change the dead time of the process. Therefore, a change in controller parameters is essential to retune the controller.

The temperature control system shown in Figure 12.43 can be represented with a simple block diagram as shown in Figure 12.44.

There are two main categories of adaptive controllers:

1. model reference adaptive controller (MRAC);
2. self-tuning controller.

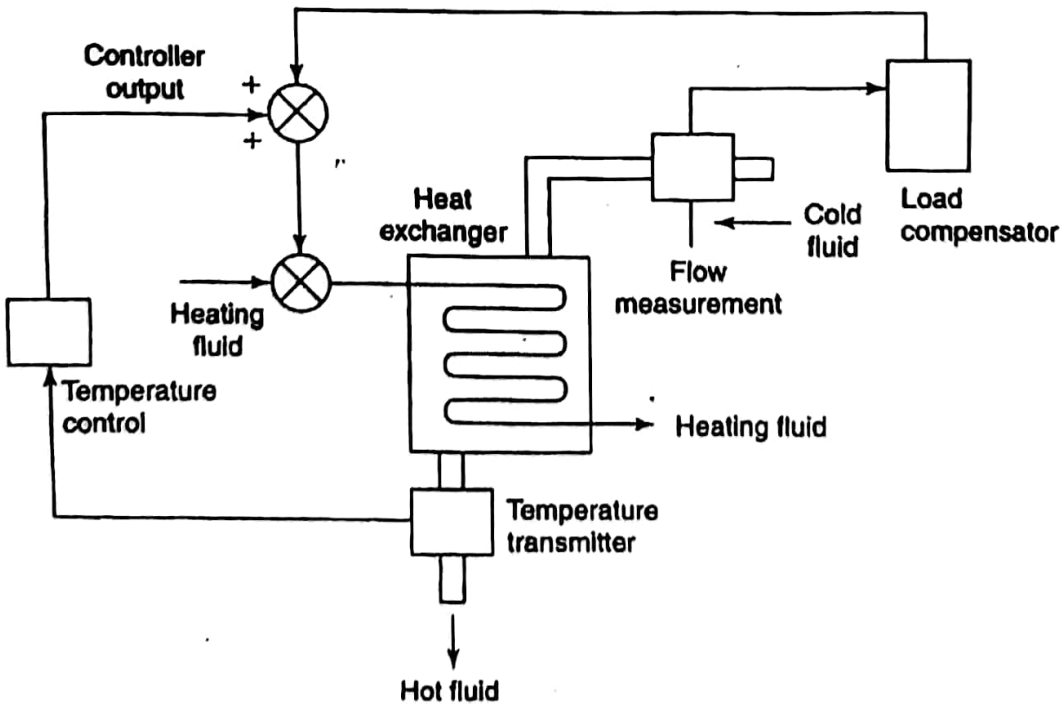


Figure 12.43 | Temperature control system with adaptive controller.

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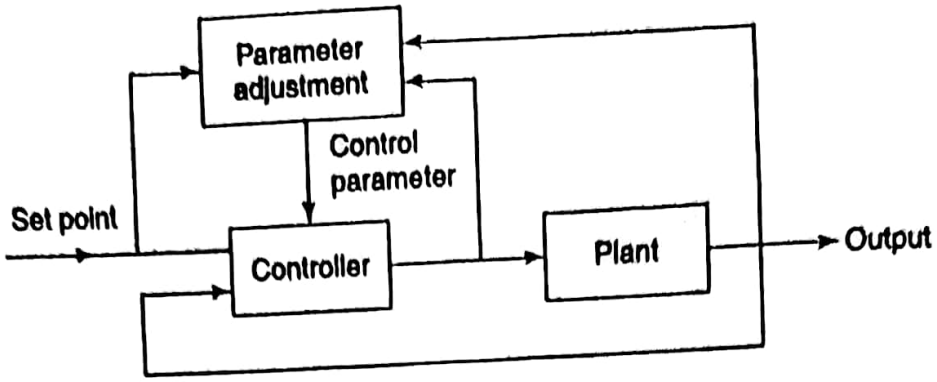


Figure 12.44 | Adaptive control system.

Model Reference Adaptive Controller (MRAC)

In MRAC, the desired performance is expressed in terms of a reference model and the adaptive controller that introduces a step change in the SP and observes the resulting process response. The controller then forms a model of the process based on the response to the step change.

The reference model is used to specify the ideal response of the adaptive control system to the external command and normally implemented in continuous time. The controller action is characterized by a number of adjustable parameters with different sets of controller parameter values as shown in Figure 12.45.

The adaptation mechanism is used to adjust the parameters in the control law. Any MRAC usually involves the following steps:

1. Choose a control law into sets of variable parameters.
2. Choose an adaptation law.
3. Analyze the convergence properties.

Self-Tuning

Self-tuning control is essentially implemented in discrete time and is an auto-tuning controller. In self-tuning controller as shown in Figure 12.46, the system continuously tunes its own parameter based on monitoring the output variable.

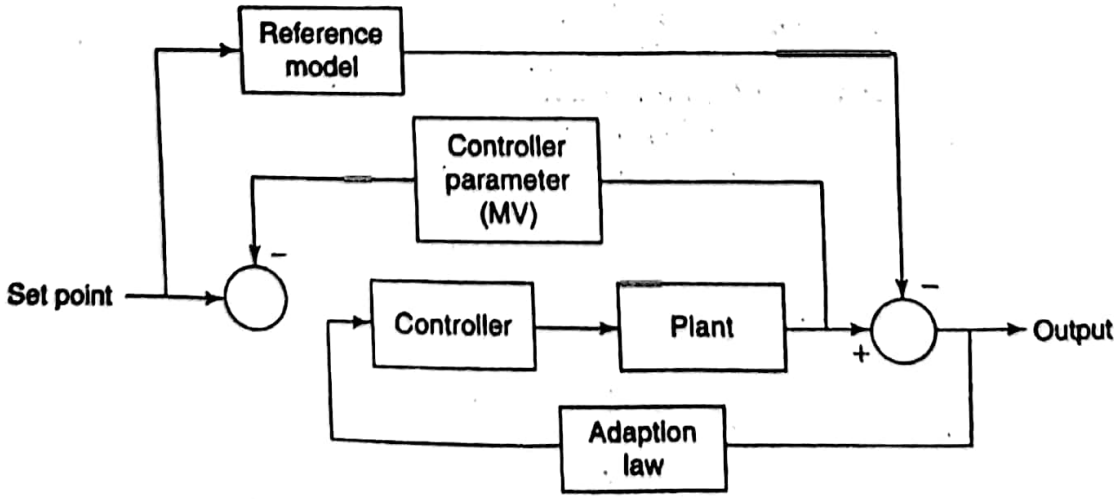


Figure 12.45 | MRAC system.

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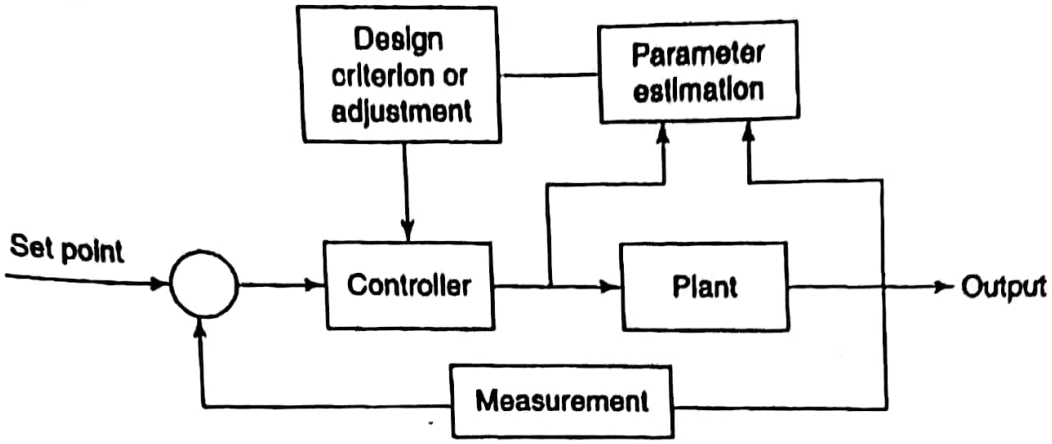


Figure 12.46 | Self-tuning controllers.

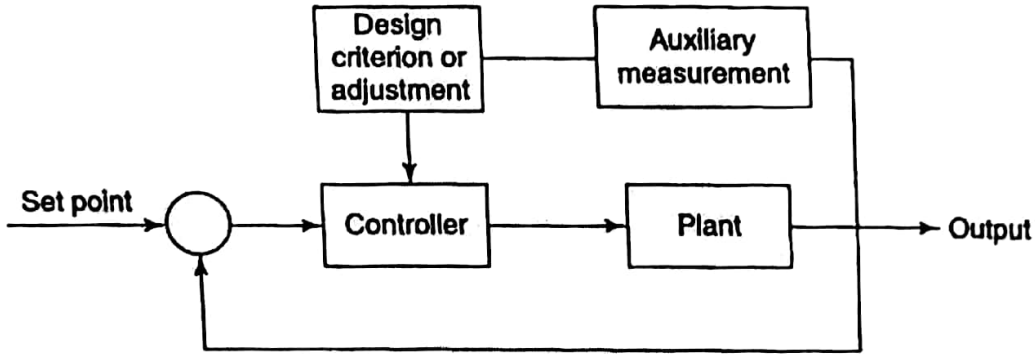


Figure 12.47 | Gain-scheduled control system.

Self-tuning control essentially consists of two elements:

1. **Parameter estimation:** This is performed online and is estimated based on the measured process input and output.
2. **Control law:** Here the parameters are estimated online and control law is based on a procedure in which the current parameter is accepted while eliminating its uncertainties. A simple method is to induce a disturbance and measure the response. The response can be studied and the control parameters are adjusted by Ziegler–Nichols method.

Another form of adaptive controller is gain-scheduled control law. In a gain-scheduled control system, the proportional gain K_p is adjusted based on auxillary measurement of process output (Figure 12.47).

13.2 Basic Structure of a PLC

A typical PLC system has five parts, as illustrated in Figure 13.5. These components are as follows:

1. central processing unit (CPU);
2. the input/output (I/O) unit;
3. the programming device;
4. memory unit.

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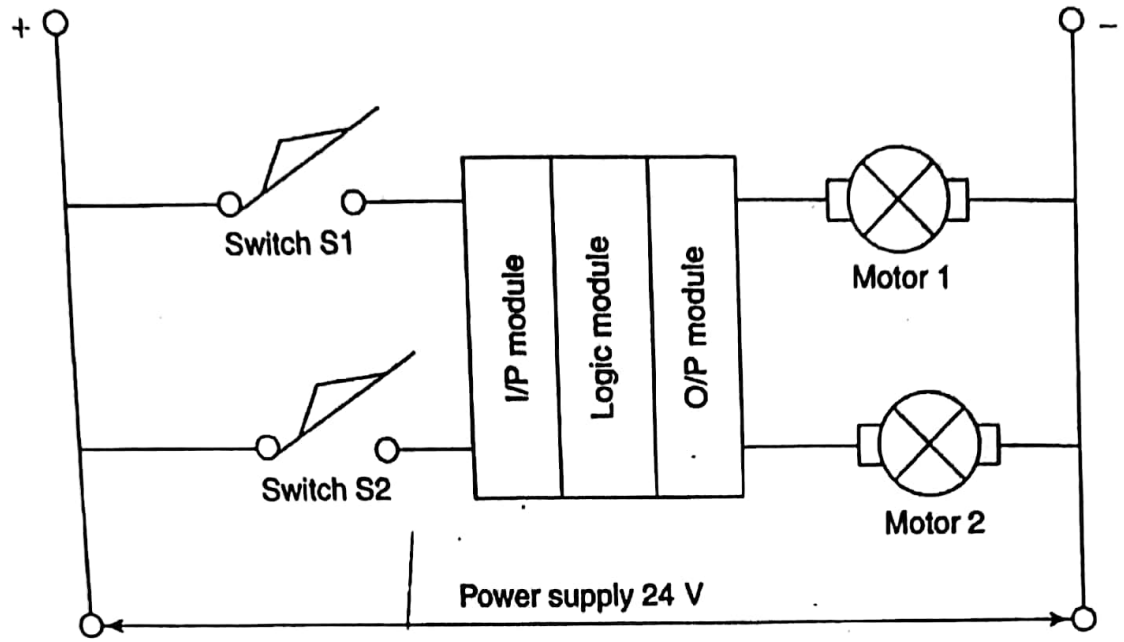


Figure 13.4 | Structure of PLC with I/O modules.

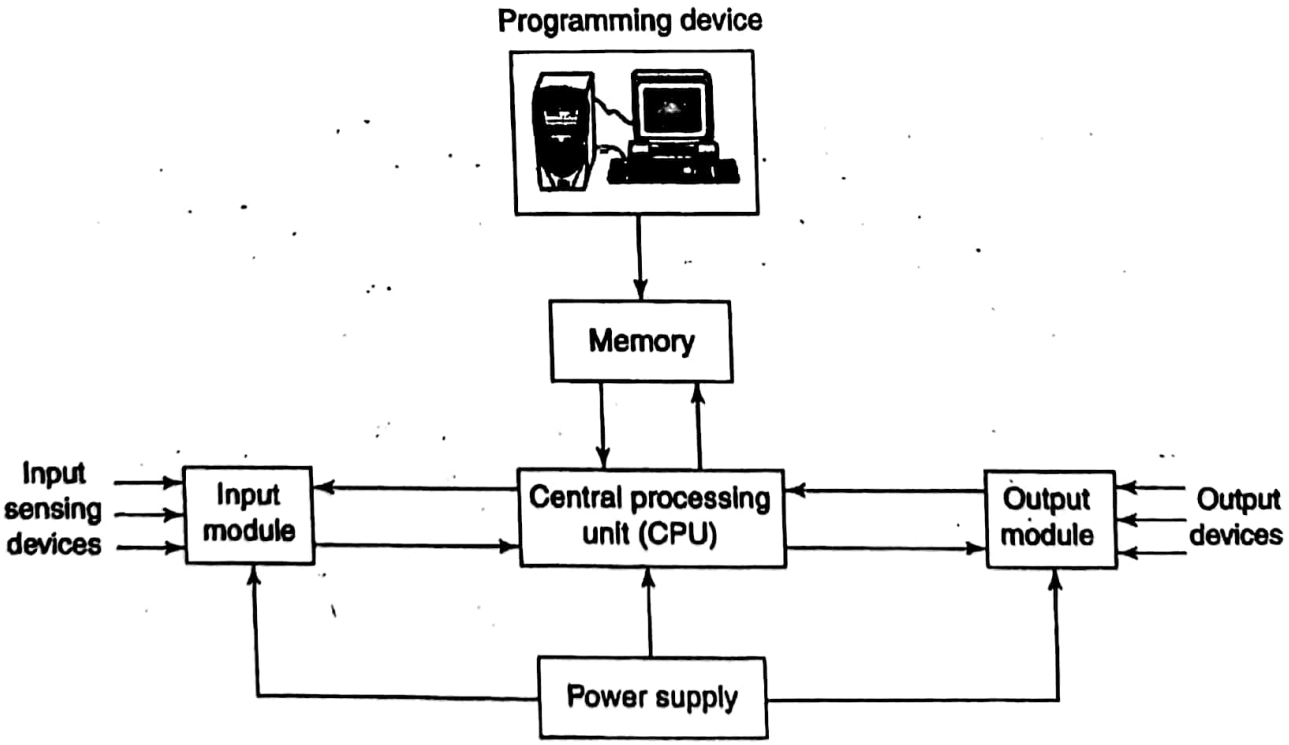


Figure 13.5 | Basic structure of a PLC system.

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Ladder Logic PLC Programming

Ladder logic (also known as ladder diagram or LD) is a programming language used to program a PLC (Programmable Logic Controller). It is a graphical PLC programming language which expresses logic operations with symbolic notation. Ladder logic is made out of rungs of logic, forming what looks like a ladder – hence the name 'Ladder Logic'.

Ladder logic is mainly for bit logic operations, although it is possible to scale a PLC analog input. Even simple bit logic operations can be beneficial in more advanced PLC programs and SCADA system programming.

The people or the organization that sets the standards for ladder logic is PLCOpen. Ladder logic is not only a programming language for PLC's. It is one of the standardized PLC programming languages. This simply means that ladder logic is described in a standard. That standard is called IEC 61131-3. But for now, the only thing you need to know is that there is a standard describing this programming language.

Introduction to Ladder Logic

To get you started with ladder logic there are a few things you should know about the programming language. You should know why ladder logic was invented because then it will be much easier for you to understand it. Especially if you have prior experience with electrical circuits and relays or some boolean logic.

Invented for Technicians

Ladder logic is a graphical programming language which means that instead of text, the programming is done by combining different graphic elements. These graphic elements are called symbols.

One of the smart things about the ladder logic symbols is that they are made to look like electrical symbols. Ladder logic was originally created for technicians, electricians, and people with an electrical background. People who are used to look at electrical diagrams and schematics.

Take a look at the symbols and see if you think they look familiar.

Just as in electrical diagrams ladder logic have symbols for contacts and relays (which are called coils in ladder logic). The symbols may look a little different from the ones you find in electrical schematics, but they have almost the same functions.

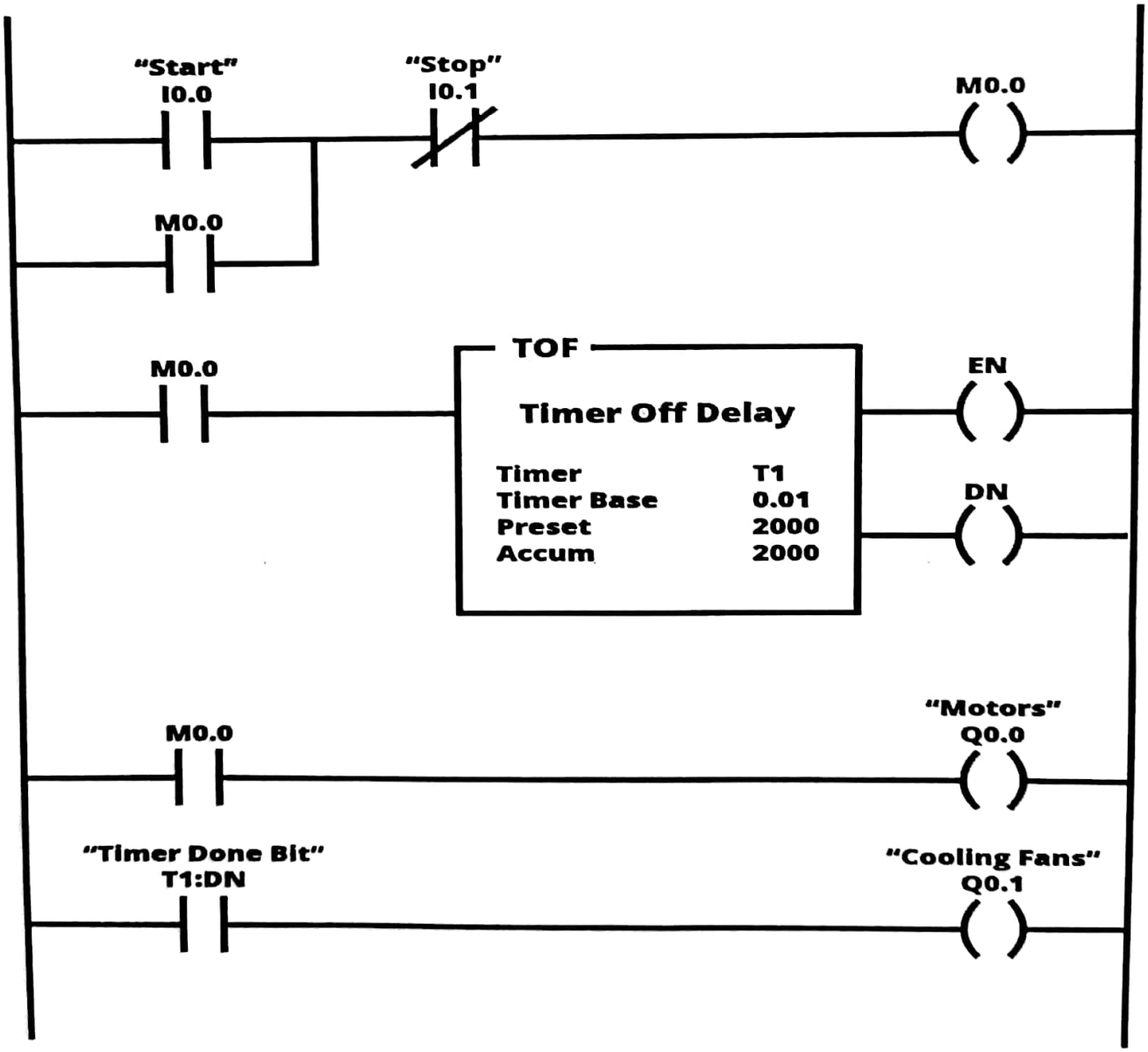
Ladder diagram, better known as ladder logic, is a programming language used to program PLCs (programmable logic controllers). This article will briefly describe what ladder logic is and go over some examples of how it functions.

Programmable logic controllers or PLCs are digital computers used to perform control functions, usually for industrial applications. Of the various languages one can use to program a PLC, ladder logic is the only one directly modeled after electromechanical relay systems.

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It uses long rungs laid out between two vertical bars representing system power. Along the rungs are contacts and coils, modeled after the contacts and coils found on mechanical relays. The contacts act as inputs and often represent switches or push-buttons; the coils behave as outputs such as a light or a motor.

Outputs don't have to be physical, though, and can represent a single bit in the PLC's memory. This bit can then be used later on in the code as another input. Contacts are placed in series to represent AND logic and in parallel when using OR logic. As with real relays, there are normally open contacts and normally closed contacts.



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15 Design of Mechatronics Systems

Learning Objectives

After completing this chapter, you will be able to:

- Gain knowledge of developing engineering and consumer products through the knowledge of mechatronics system.
- Understand the integration of various systems through electronics, mechanical systems and computers.
- Design mechatronics systems for given application.
- Develop skills for designing mechatronics systems and products.

This chapter presents design approach and case studies of mechatronics systems. Examples of autopilot system, car parking system, engine management system, high speed titling training, autonomous mobile robot, coin counter and antilock braking system are discussed. Further, a brief outline of future trends in mechatronics system is given.

15.1 Introduction

The design process starts with a felt need or a perceived one by the ingenuity of the designer. Analysis of the problem and understanding the situation right to the last point or detailing the problem is very basic for the success of the proposal.

Specification of the requirements needs to be prepared first. The following are some of the statements about the problem: Mass and dimensions of design, type and range of motion required, accuracy of the element, input and output requirements of elements, interfaces, power requirements, operating environment, relevant standards, code of practice, etc.

Next stage is the conceptualization and synthesis stage. The conceptualization step is to determine the elements, mechanisms, materials and process of configuration that in some or other combination results in a design that satisfies the need. This is the key step for employing inventiveness and creativity. Synthesis is the process of taking elements of the concept, sized and dimensioned in the proper way, and arranging them in the proper order. This is followed by selection of one alternative and finalizing that. Next steps are one of detailed designs and coming out with working drawings.

15.2 Mechatronics Approach to Design

In a mechatronics approach, mechanical, electronics, computer technology and control engineering principles are included to design a system. For example, the design of a weighing scale might be considered only in terms of the compression of springs and a mechanism used to convert the motion of spring into rotation of shaft and hence movements of a pointer across a scale. In this design, measurement of weight is dependent on

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the position of weight on the scale. If we want to overcome the aforesaid problem, other possibilities can be considered. In mechatronics design, the spring might be replaced by load cells with strain gauges and output from them used with a microprocessor to provide a digital readout of the weight on a light-emitting diode (LED) display. This scale might be mechanically simpler, involving fewer components and moving parts. But the software is somewhat complex.

Similarly, the traditional design of the temperature control for a central AC system involves a bimetallic thermostat in a closed-loop control system. The basic principle behind this system is that the bending of the bimetallic strip changes as the temperature changes and is used to operate an ON–OFF switch for the temperature control of the AC system. The same system can be modified by a mechatronics approach. This system uses a microprocessor-controlled thermocouple as the sensor. Such a system has many advantages over a traditional system. The bimetallic thermostat is less sensitive compared to the thermodiode. Therefore, the temperature is not accurately controlled. Also, it is not suitable for having a different temperature at a different time of the day because it is very difficult to achieve. But the microprocessor-controlled thermodiode system can overcome foresaid difficulties and gives precision and programmed control. This system is much more flexible. This improvement in flexibility is a common characteristic of the mechatronics system when compared with a traditional system.

In general, the mechatronics design process begins by a macro design stage and the requirements regarding the system behavior and determination of functional parameters. The approach to mechatronics design process can be well understood from the block diagram shown in Figure 15.1.

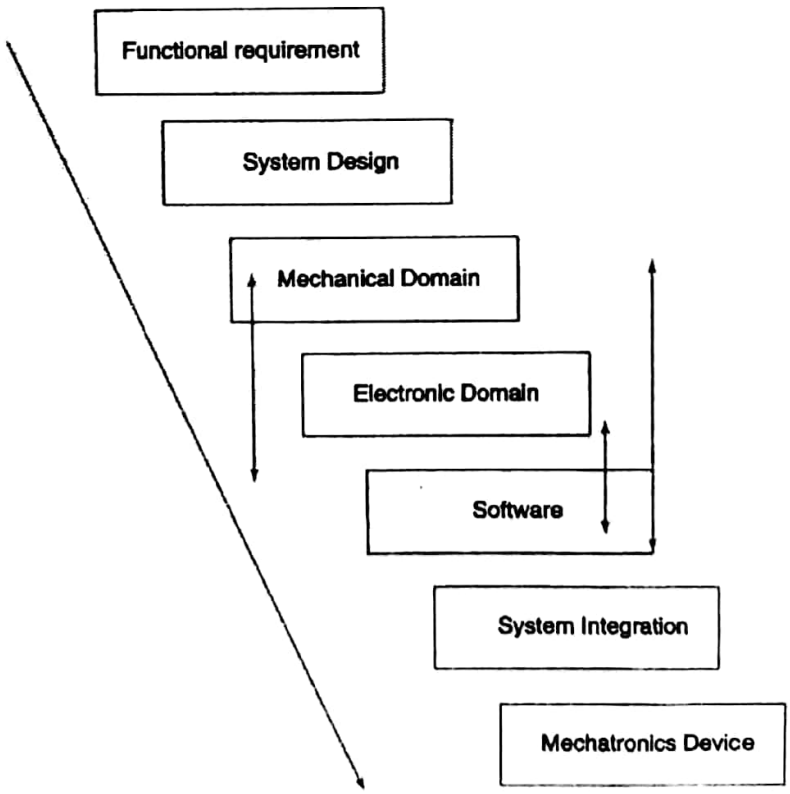


Figure 15.1 | The mechatronics design process.

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15.3 Case Examples

Boat Autopilot

The objective of an autopilot system is to automate the movement of the boat once the direction and destination are fixed. The autopilot takes over and goes on correcting the course of drive continuously so that the direction does not change substantially. Though the autopilot cannot make substantial changes in the direction of the boat all of a sudden, it definitely corrects the course on a continuous basis and keeps the variation within a margin. This eliminates the probability of running on a wrong course for a longer time and increases the fuel consumption.

The boat autopilot is a very good example of an integrated mechatronics system. Figure 15.2 shows a general arrangement and the schematic. The user has to set up the boat using the landmark or boat's mariner's compass and then push the autobutton ON. Changes and trimming adjustments on direction of the course (route) can be made from the control unit. The direction of the course is measured by a compass linked to a single microprocessor microcontroller. The output of the computer through a power IC board is to a DC motor. The mechanical drive is taken through a double reduction toothed belt drive on to a screw which propels the hollow ram (used to turn the rudder angle) using a low friction ball nut. Ram movement is calculated by integrating motor emf and feedback is from the headings of the boat itself.

Mechanical design should meet the requirements of the tiller force generated at specific angles and rate of rotation, taking into account the hydrodynamic forces due to particular envelops of rudder configuration and forward speed. Based on this the size of the components, required power levels of the driver and associated power electronics are outlined. This product is a very good example of an integrated mechatronics design application.

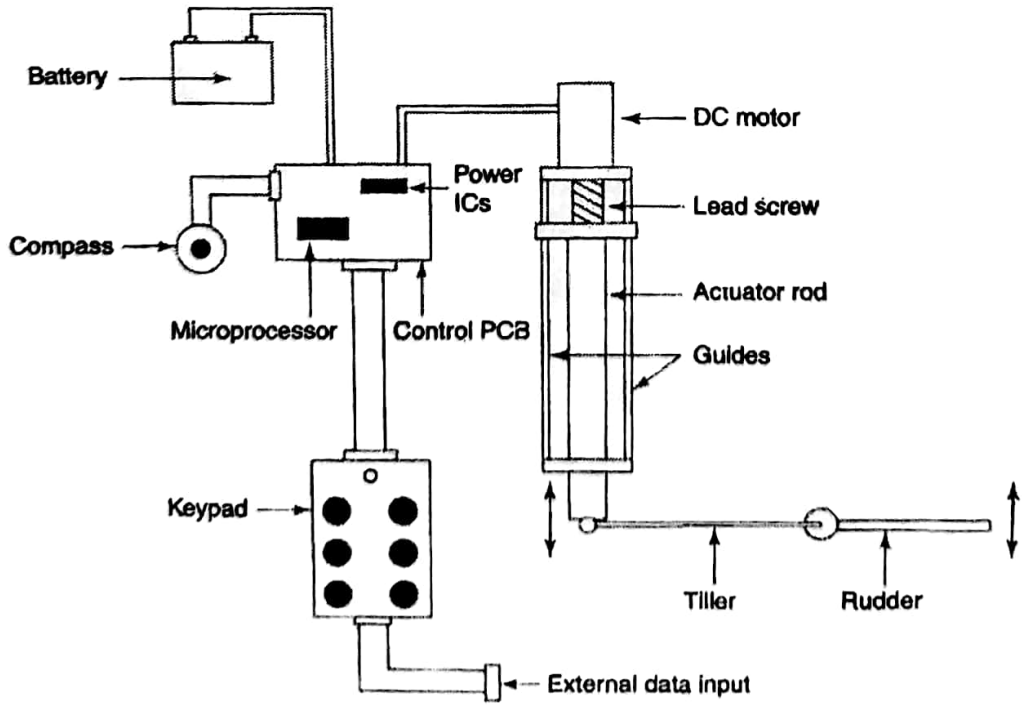


Figure 15.2 | Schematic arrangement of boat autopilot.

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High-Speed Tilting Trains

When a train is negotiating a corner the passengers experience a lateral force that is proportional to v^2/r, where v is the velocity of the train and r the radius of the curve. This causes severe discomfort when it exceeds a limit. This also causes radial forces on the track and the track wears out. The track wear-out issue can be overcome by adding this parameter into the design aspect but the discomfort due to the radial force remains. Conventional solution to this problem has been to make the track inclined so that forces are normal to the floor of the carriage body. However, if the speed of the train is greater or lower than the speed for which the track inclination is designed, then again this phenomenon causes discomfort and lays extra stress on the track in the reverse direction. Some tracks are custom made for certain trains such as the bullet train and the tracks are very specifically designed for the designed speed of the train so that such effects are minimized. The problem of constraint on the speeds that can be attained is prominent when the train has to be run on the existing tracks and the track inclinations that exist already.

Figure 15.3 shows an alternative to this problem, known as tilting trains. Here the carriage floor is tilted when negotiating a bend so that the forces are normal to floor of the carriage, and causes least discomfort to the passengers. The degree of tilt is controlled to match the speed of the train. This train uses active suspension controlled by an onboard computer. Lateral actuators act in conjunction to provide the tilting force in accordance with the speed. Controlled variable rate springs and dampers act to provide additional control over the motion. Operation of the tilting mechanism is controlled by sensor information which is in the form of a pendulum constrained to swing in a plane of the carriage cross section as shown in Figure 15.4.

The sensor system consists of sensors and pendulum. As the train takes the bend, the pendulum gets displaced outward toward the circumference of the bend and the tilt angle of the carriage would be adjusted to bring back the displacement of the pendulum relative to the carriage vertical within defined limits. Information on speed and lateral acceleration is used in association with the predefined program to control lateral actuators (hydraulic cylinders) and variable rate springs and dampers.

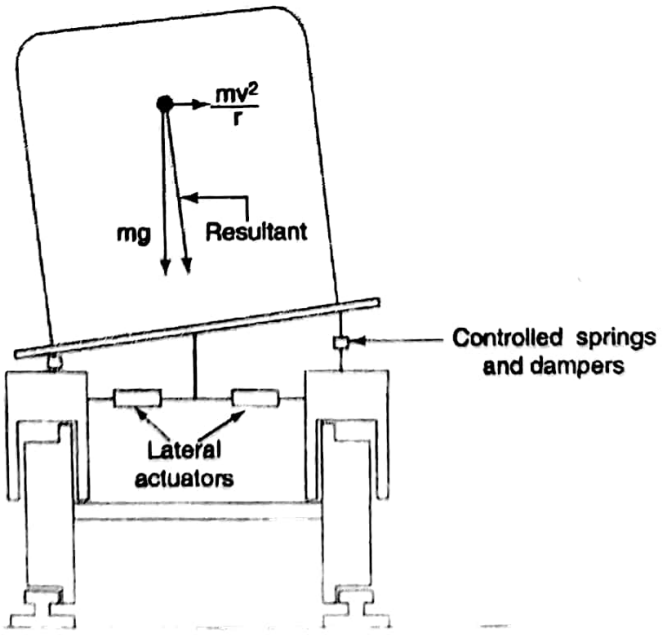


Figure 15.3 | Centrifugal and resultant forces in a tilting train.

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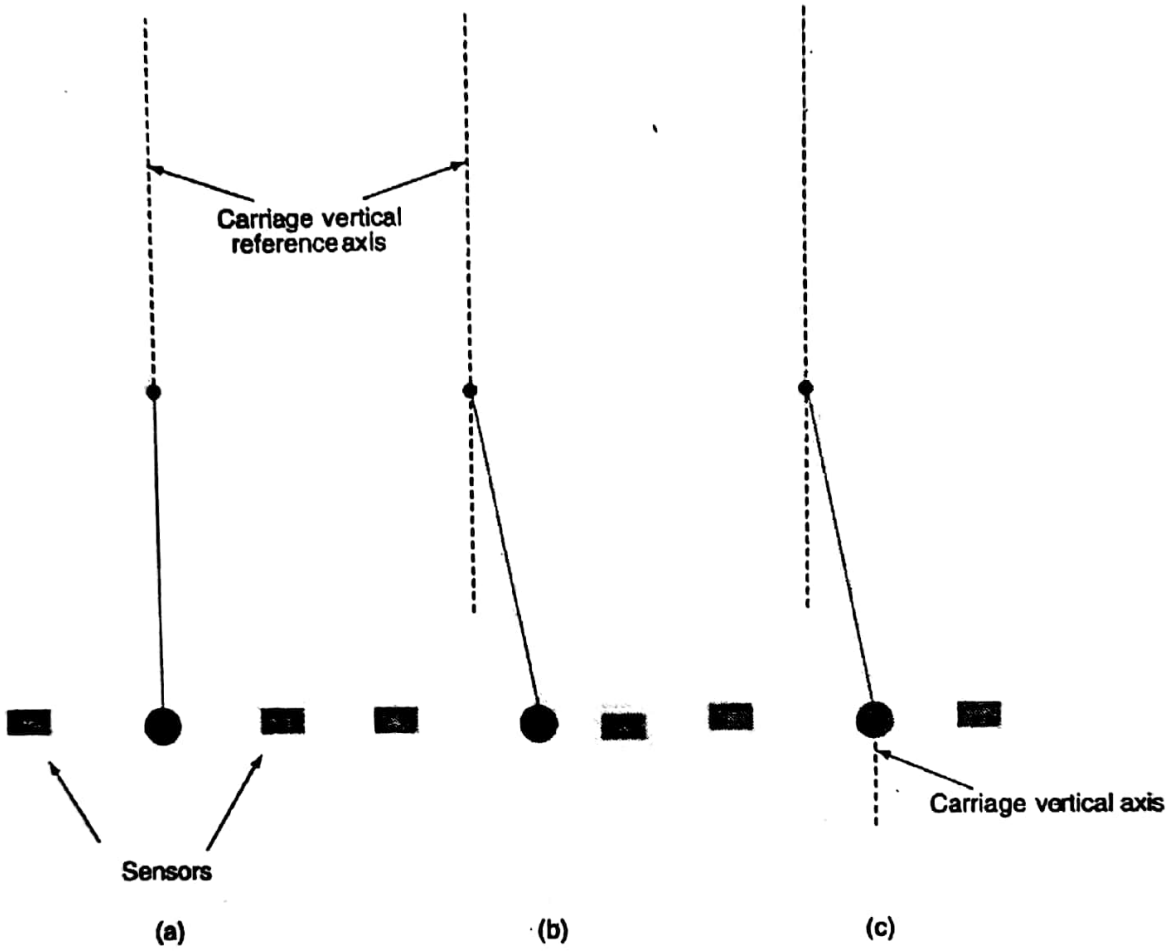


Figure 15.4 | Tilt control using a pendulum. (a) Pendulum in the plane of the cross section when the train is going on a straight track. (b) Pendulum as the carriage entered the bend. (c) Carriage is tilted to adjust pendulum within limits relative to the carriage vertical.

Figure 15.5 depicts the control of the tilting train. Tilting trains have been installed in UK, Italy and Sweden.

Automatic Car Park System

Consider an automatic car park system with barriers operated by electrical pushbutton. The system uses a PLC for its operation. There are two barriers used, namely in-barrier and out-barrier. In-barrier opens when the pushbutton is pressed while out-barrier opens when a car is detected in front of it. Figure 15.6 shows a schematic arrangement of an automatic car park barrier. It consists of a barrier which is pivoted at one end, two solenoid valves *A* and *B* and a pneumatically controlled piston cylinder arrangement. Solenoid operated valves are used to control the movement of the piston. Solenoid valve *A* is used to move the piston upward in turn barrier whereas solenoid *B* is used to move the piston downward. Limit switches are used to detect the foremost position of the barrier. When pushbutton *A* is pressed, current flows through solenoid *A*, and the piston in the cylinder moves upward causing the barrier to rotate about its pivot. The barrier now opens to allow a car through.

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The central control unit generally consists of two microcontrollers, both active simultaneously, to add some redundancy to the system. The software that runs in the ECU has a number of functions. Most notably, the algorithms drive the HCU as a function of the inputs or control the brakes depending on the recorded wheel spin. Apart from this, the software is also needed to process the incoming information, for example the signals from the sensors. The control algorithms and the signal processing software certainly fall in this category and get a higher priority than the diagnosis and the testing software.

15.4 Future trends – Smart Homes

Accenture Labs (multi-national company) is aiming its research for creation of smart homes which are basically meant to make the lives of the old and infirm comfortable. Smart homes of the future will not only feature designer fabrics and furniture on household appliances, but they will also be filled with clever technology that takes a greater interest in our daily life. Researchers at the technology consultancy Accenture are working on ways to help homes watch what their occupants are doing.

The work is aimed at helping older people by spotting when they get into difficulties, to diagnose health problems before they become serious and to combat loneliness by making it easier to keep in touch with their family. Eventually the projects could produce products that help almost anyone stay healthy or stay in contact with friends.

Dumb Domicile

By 2050, according to UN estimates, about 20% of people will be aged 60 or over. In developed nations, the figure could climb as high as 33%. Statistics showed that *carers* were two to three times more likely to need drugs to cure depression, anxiety and insomnia than any other group.

To help people cope, researchers are concentrating on five main projects:

1. persuasive mirrors;
2. connective tables;
3. shared scrap books;
4. interactive pictures;
5. activity monitoring.

The persuasive mirror manipulates images of a person in real time depending on what the person has been doing all day. This could be used to encourage people to live healthier lives by showing what would happen to their appearance if they did no exercise and did not watch what they ate.

The connective table would use video-conferencing and projectors to let people play games such as draughts or chess even though they were in different locations.

Shared scrap books would let individual family members contribute images, messages and video to a single electronic journal that anyone could look at and flick through.

Snap and Swap

Interactive pictures would be a framed screen that acted as a direct channel to the person that it depicted. It is designed for older people who do not, or cannot, learn to use a PC to communicate with more tech-savvy offspring and grandchildren. It is extremely hard for an 80-year-old person to go back to sit at a school desk and learn about computers. Just standing in front of the picture can open a channel without doing any funny stuff on the keyboard. E-mail or instant messages sent to interactive picture would appear as a virtual post-it note that could be read off the screen. Recorded voice and video messages could be played back via the screen. When fitted with a small camera it could also act as a videophone for live chats.

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Watching Brief

Activity monitoring involves placing a series of cameras around a home that watches what a person does, where he goes and how he gets there. Software would analyze the video shot by the cameras to monitor such things as facial expressions, posture and gait, focus of attention, the object someone interacts with and a person's trajectory. The system can also watch someone's center of gravity to work out if the person has fallen and could then alert doctors, carers and family to mobilize help. Monitoring could also give clues to a person's emotional and physical state. It is also possible that the effects of diseases such as Alzheimer's are often revealed by the way someone behaves long before other signs become apparent.

Sofas Get Smart for Hi-Tech Homes

Couch potatoes could soon be turning on their TVs, activating their answering machines and automatically ordering takeaways – simply by settling down on "smart sofas".

Dublin scientists have shown off the latest thing in "intelligent furniture" that could be heading for hi-tech homes of the future – a comfy couch. Programmable microchip sensors, connecting the sofa's legs to a computer, find out who is sitting on the sofa, by measuring their weight and switch on the required controls to match the person's personal choices on household appliances. Scientists also hope the sofa will benefit the sick or the infirm. It is able to give a verbal welcome and switch on household appliances. The scientists are also developing sports equipment that provides critical analysis of technique.

Ethics as Design Constraint

Future mechatronics design has to heavily address the constraints imposed upon the design process by the ethical standards that it has to adhere to. In its role as driver for design, ethics can act as multiple constraints on the design process. Out of their concern for safety, engineers use higher factors of safety than sometimes warranted. If it is known that a bridge has to be designed for a factor of safety of 6, then the selection of materials and design techniques get highly limited. The basic reason, the factor of safety exists, is that there exists an ethical code which holds life, safety, health, environment and welfare of public good the paramount. The code of ethics would seem to drive engineers to be as conservative as possible in designs which would harm many people in case of failure. Environmental concerns again are constraints in the design process. For example, the exhaust gases from an automobile system have to consider the environmental impact. The air-conditioning systems must use refrigerants which do not use CFCs that may harm the ozone layer. These constraints tend to be very costly. Many engineering societies (e.g. Institution of Electronic and Electrical Engineers and American Society of Civil Engineers) have amendments to their codes to ensure that their constituents have a professional obligation for environmental protection.

SUMMARY

1. Mechatronics design process begins by a macro design stage and the requirements regarding the system behavior and determination of functional parameters.
2. The boat autopilot is a very good example of an integrated mechatronics system and is used to automate the movement of the boat without manual operator once the direction and destination are fixed.
3. High-speed tilting train design is based on tilting mechanism that is controlled by sensor information which is in the form of a pendulum constrained to swing in a plane of the carriage and essentially take off discomfort to the passengers due to lateral force when a train is negotiating cornering.
4. PLCs can be effectively used to control of an automatic car parking system.

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Unit-6

1. What is a PLC? How it is different from microcontroller? What are the advantages of PLC compared to a microcontroller?
2. Explain with the help of ladder rungs the jump control mechanism in a programmable and logic controller (PLC).
3. Classify the different types of Process Controllers? Distinguish them in detail.
4. Explain future trends of mechatronics system.

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