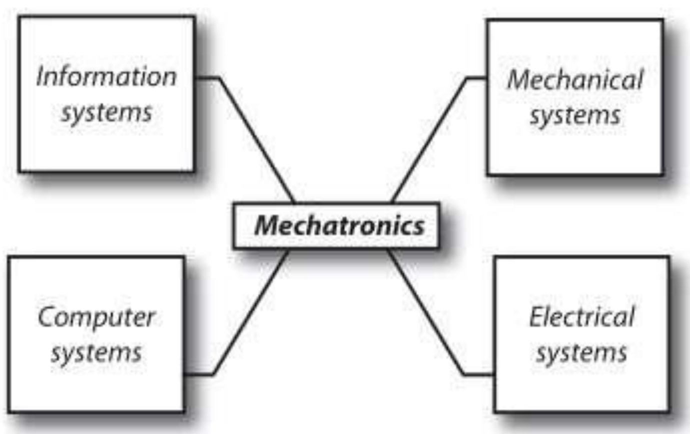
# Introduction to Mechatronics

**What is Mechatronics?**

Mechatronics is the field of study concerned with the design, selection, analysis, and control systems that combine mechanical elements with electronic components, including computers and/or microcontrollers. Mechatronics topics involve elements from mechanical engineering, electrical engineering, and computer science, and the subject matter is directly related to advancements in computer technology. All the definitions agree that mechatronics is an interdisciplinary field, in which the following disciplines act together:

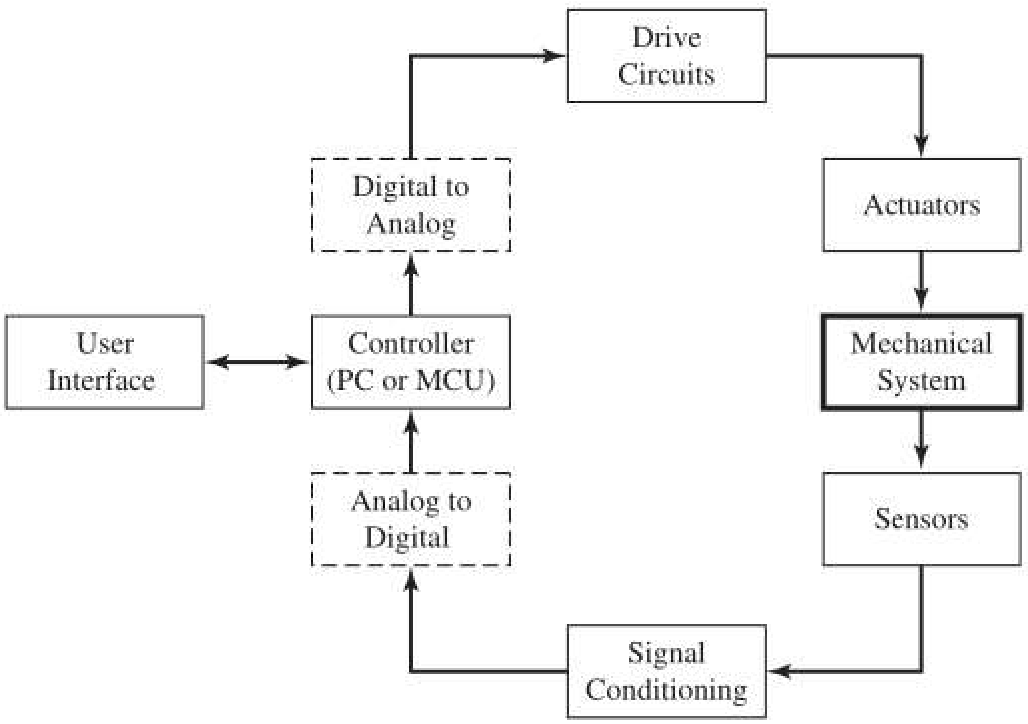
• Mechanical systems (mechanical elements, machines, precision mechanics);
• Electronic systems (microelectronics, power electronics, sensor, and actuator technology); and
• Information technology (systems theory, automation, software engineering, artificial intelligence).




Mechatronics constituents

In 1969 the term ‘mechatronics’ was first coined by the Japanese scientist Yoshikaza. The trademark was accepted in 1972 (i.e., ‘mecha’ from mechanical engineering and ‘tronics’ from electrical or electronic engineering).

A block diagram of a typical mechatronic system is shown below mechatronic system has at its core a mechanical system which needs to be commanded or controlled. Such a system could be a vehicle braking system, a positioning table, an oven, or an assembly machine. The controller needs information about the state of the system. This information is obtained from variety of sensors, such as those that give proximity, velocity, temperature, or displacement information. In many cases, the signals produced by the sensors are not in a form ready to be read by the controller and need some signal conditioning operations performed on them. The conditioned, sensed signals are then converted to a digital form (if not already in that form) and presented to the controller.




Typical components of a mechatronics system

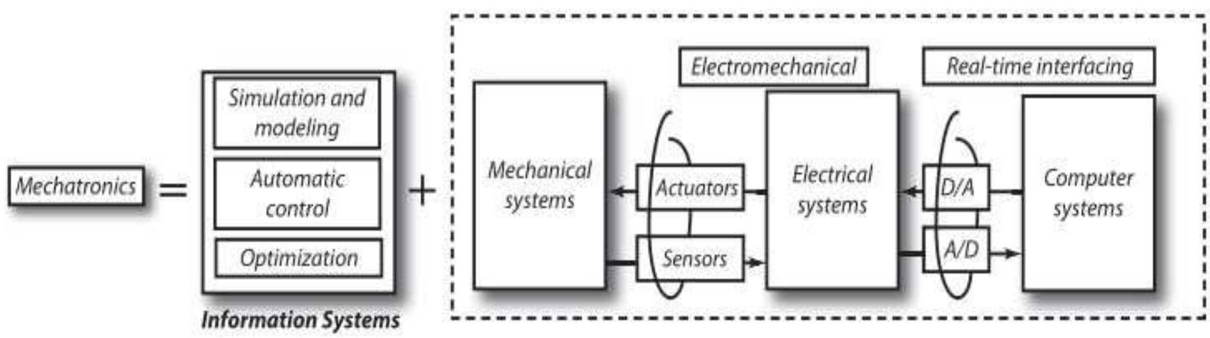
In many cases, the command signals to the actuators are first converted from a digital to an analog form. Amplifiers implemented in the form of drive circuits also can be used to amplify the command signals sent to the actuators. The actuator is the mechanism that converts electrical signals into useful mechanical motion or action.

A mechatronic system integrates mechanical components, electronic components, and software implemented either on a PC or MCU to produce a flexible and intelligent system that performs the complex processing of signals and data. In many cases, a mechatronic system can be used to improve the performance of a system beyond what can be achieved using manual means. An example includes the speed control of rotating equipment. In some cases, a mechatronic system is the only means by which that system can operate (such as the control of magnetic bearings and in nano-positioning control applications).

Key Elements of Mechatronics

The study of mechatronic systems can be divided into five areas of specialty:
1. Physical systems modeling
2. Sensors and actuators
3. Signals and systems
4. Computers and logic systems
5. Software and data acquisition

Mechatronics is the result of applying information systems to physical systems. The physical system consists of mechanical, electrical, and computer systems as well as actuators, sensors, and real-time interfacing.




**Mechatronics key elements**

## Historical Development and Definition of Mechatronic Systems

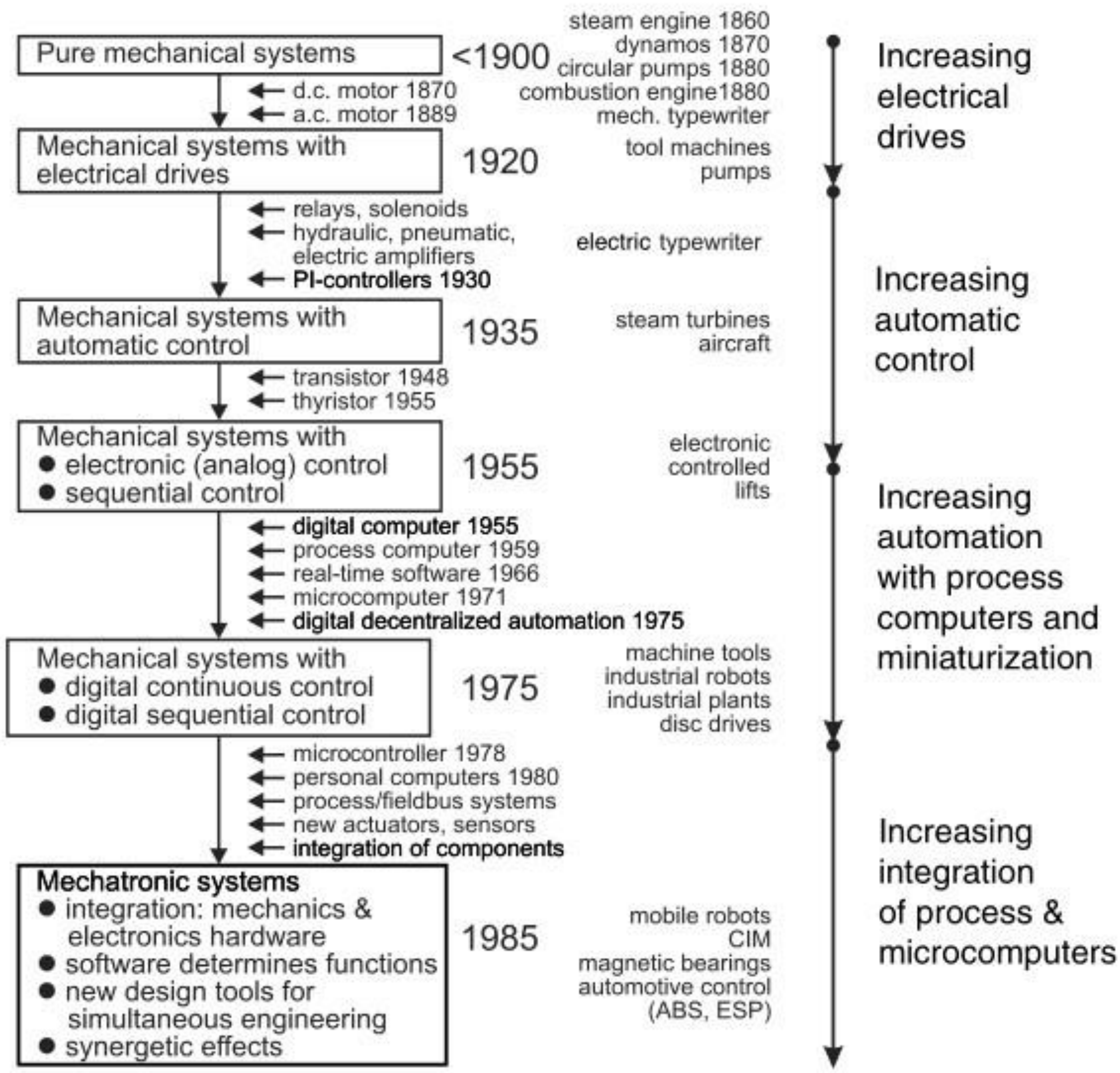
In several technical areas the integration of products or processes and electronics can be observed. This is especially true for mechanical systems which developed since about 1980.

These systems changed from electro-mechanical systems with discrete electrical and mechanical parts to integrated electronic-mechanical systems with sensors, actuators, and digital microelectronics. These integrated systems, as seen in Table below, are called mechatronic systems, with the connection of MECHAnics and elecTRONICS.

In reference, a preliminary definition is given: “Mechatronics is the synergetic integration of mechanical engineering with electronics and intelligent computer control in the design and manufacturing of industrial products and processes”. All these definitions agree that mechatronics is an interdisciplinary field, in which the following disciplines act together:

• Mechanical systems (mechanical elements, machines, precision mechanics)
• Electronic systems (microelectronics, power electronics, sensor, and actuator technology) and
• Information technology (systems theory, automation, software engineering, artificial intelligence)

Historical Development of Mechanical, Electrical, and Electronic Systems




**Examples of Mechatronics Systems**

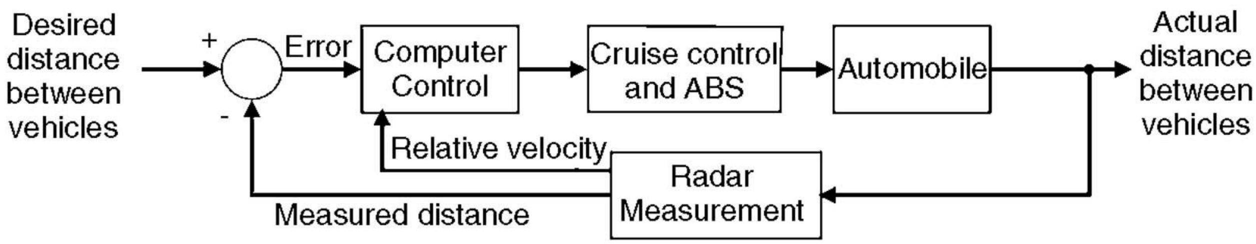
Modern society depends on mechatronic-based systems for its conveniences and luxurious standard of living. From intelligent appliances to safety features in cars (such as air bags and anti-lock brakes), mechatronic systems are widely used in everyday life. The availability of low-cost, compact, and powerful processors in the form of MCUs accelerated the widespread use of mechatronic systems. An example is the use of embedded controllers to control many of the devices in a vehicle. A list of such applications is shown in Table below

**Listing of sample applications of mechatronic systems in vehicles**

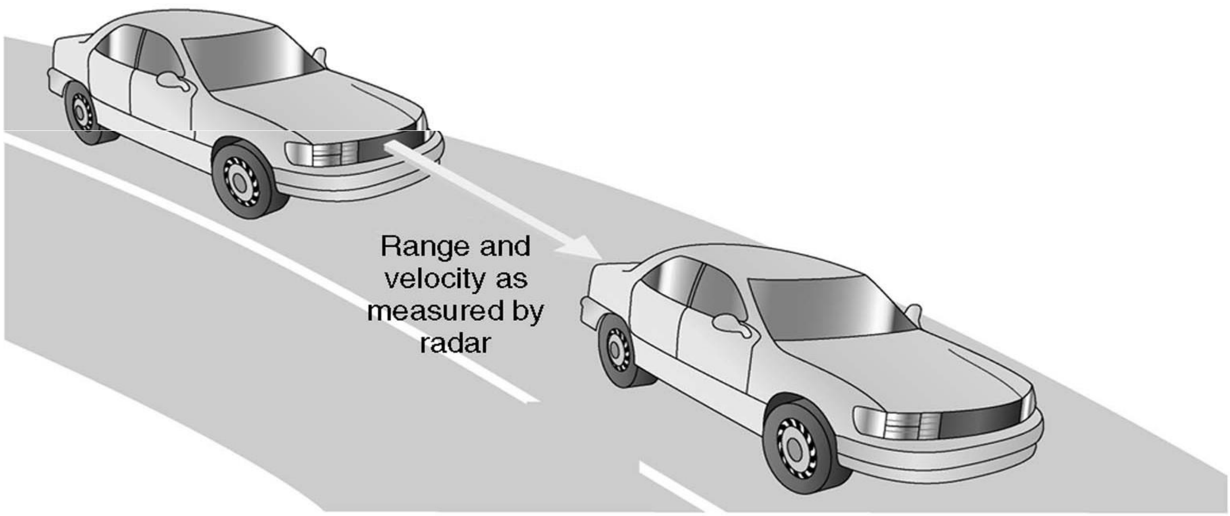
| Application Area | | |
|---|---|---|
| **Safety** | **Comfort** | **Power Train** |
| • Airbag system | • Door locks | • Engine controls |
| • Anti-lock breaking system | • Keyless entry system | • Fuel pump controls |
| • Daytime running light | • Heating system controls | • Fuel sensing controls |
| • Electronic stability controls | • Seat positioning controls | • Gearbox controls |

Example:

Millimeter wave radar technology has recently found applications in automobiles. The millimeter wave radar detects the location of objects (other vehicles) in the scenery and the distance to the obstacle and the velocity in real-time. Figure below shows an illustration of the vehicle-sensing capability with millimeter-wave radar. This technology provides the capability to control the distance between the vehicle and an obstacle (or another vehicle) by integrating the sensor with the cruise control and ABS systems. The driver is able to set the speed and the desired distance between the cars ahead of him. The ABS system and the cruise control system are coupled together to safely achieve this remarkable capability.




(a)




(b)

Using radar to measure the distance and velocity to autonomously maintain desired distance between vehicles.

**Sun-Tracking Control of Solar Collectors**

Figure below shows a solar collector field. Also, shows a conceptual method of efficient water extraction using solar power. During the hours of daylight, the solar collector would produce electricity to pump water from the underground water table to a reservoir (perhaps on a nearby mountain or hill), and in the early morning hours, the water would be released into the irrigation system. One of the most important features of the solar collector is that the collector dish must track the sun accurately. Therefore, the movement of the collector dish must be controlled by sophisticated control systems. The block diagram of Figure below describes the general philosophy of the sun-tracking system together wi.th some of the most important components. The controller ensures that the tracking collector is pointed toward the sun in the morning and sends a "start track" command.

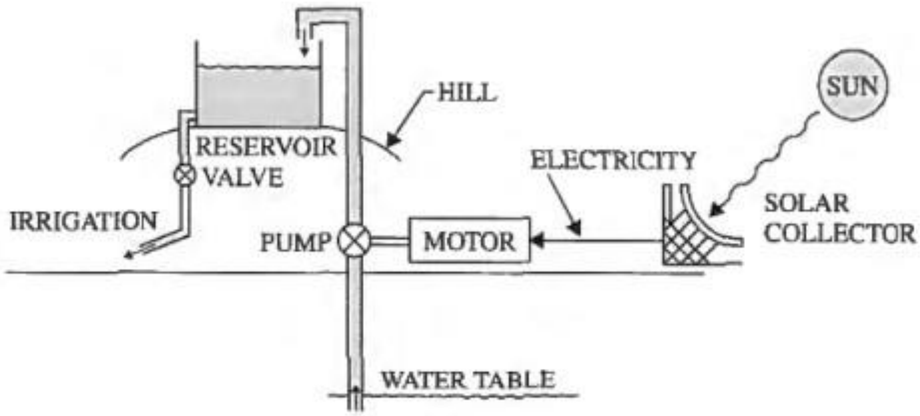



**Figure** Conceptual method of efficient water extraction using solar power.

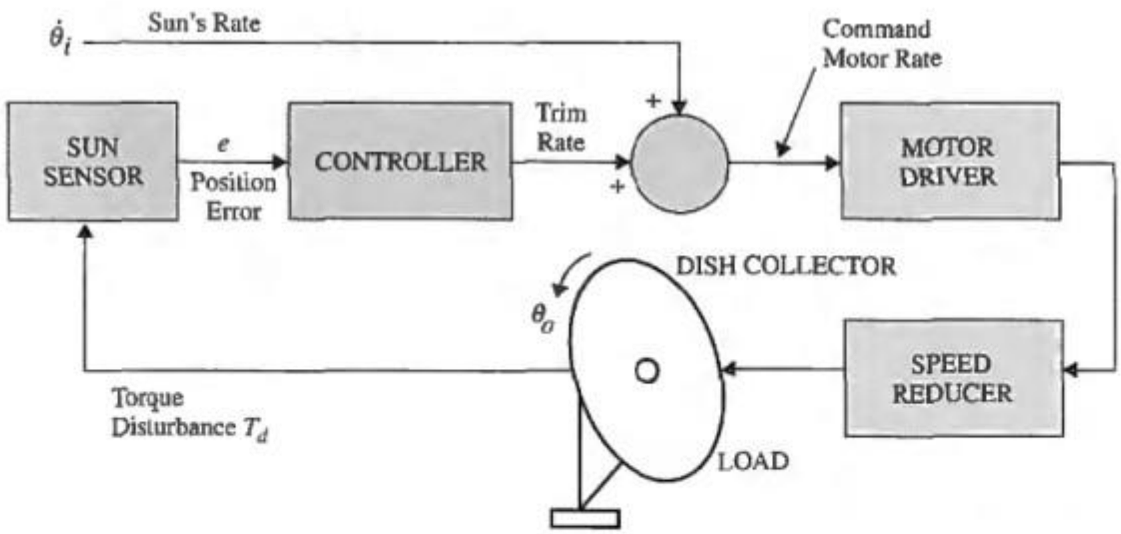



**Figure** Important components of the sun-tracking control system.

## Functions of Mechatronic Systems

Mechatronic systems permit many improved and new functions. This will be discussed by considering some examples.

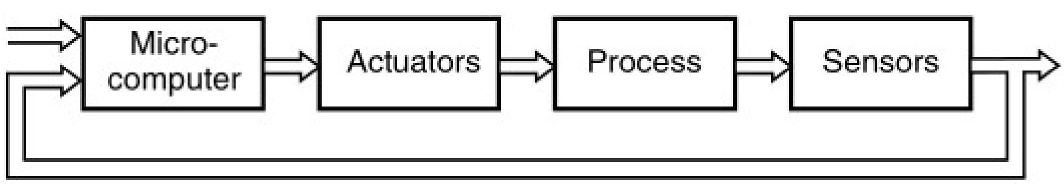
**1. Division of Functions between Mechanics and Electronics**
For designing mechatronic systems, the interplay for the realization of functions in the mechanical and electronic part is crucial.

2**. Improvement of Operating Properties**
By applying active feedback control, precision is obtained not only through the high mechanical precision of a passively feed-forward controlled mechanical element, but by comparison of a programmed reference variable and a measured control variable.

**3. Addition of New Functions**
Mechatronic systems allow functions to occur that could not be performed without digital electronics. Examples are time-dependent variables such as slip for tires, internal tensile, temperatures, slip angle and ground speed for steering control of vehicles, or parameters like damping, stiffness coefficients, and resistances.

## Ways of Integration

Figure below shows a general scheme of a classical mechanical-electronic system. Such systems resulted from adding available sensors, actuators, and analog or digital controllers to mechanical components.




**General scheme of a (classical) mechanical-electronic system.**

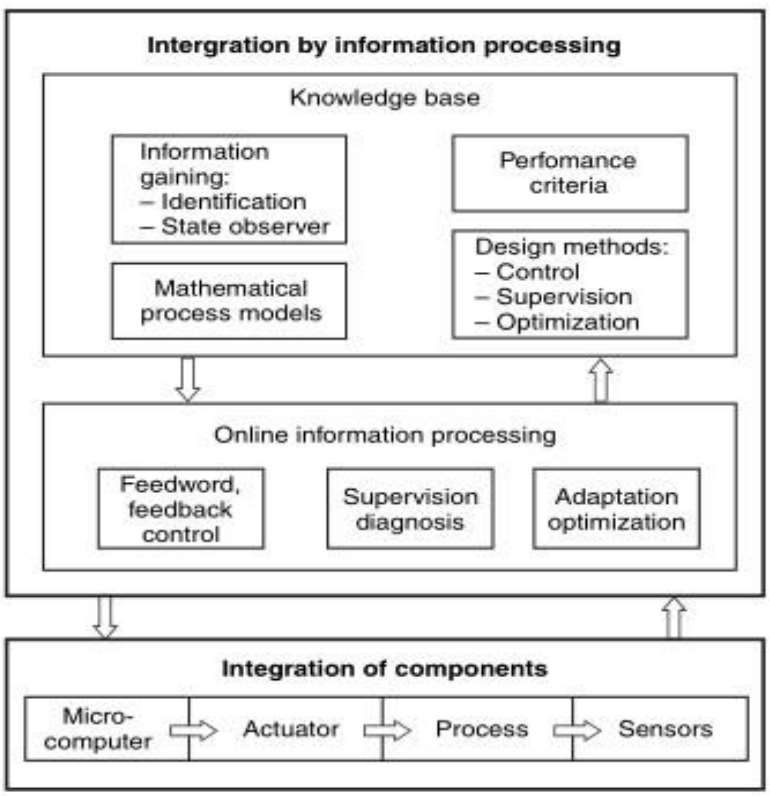
The integration within a mechatronic system can be performed through the integration of components and through the integration of information processing.

**1. Integration of Components (Hardware)**

The integration of components (hardware integration) results from designing the mechatronic system as an overall system and imbedding the sensors, actuators, and microcomputers into the mechanical process, as seen in Figure below. This spatial integration may be limited to the process and sensor, or to the process and actuator.

**2. Integration of Information Processing (Software)**

The integration of information processing (software integration) is mostly based on advanced control functions. Besides a basic feed-forward and feedback control, an additional influence may take place through the process knowledge and corresponding online information processing, as seen in Figure below. This means a processing of available signals at higher levels, including the solution of tasks like supervision with fault diagnosis, optimization, and general process management




Ways of integration within mechatronic systems.

## Modeling and Design

A design may use excessive safety factors and worst-case specifications. This will not provide an optimal design or may not lead to the most efficient performance. Design for optimal performance may not necessarily lead to the most economical (least costly) design, however.
When arriving at a truly optimal design, an objective function that takes into account all important factors or criteria (performance, quality, cost, speed, ease of operation, safety, environmental impact, etc.) has to be optimized. A complete design process should generate the necessary details of a system for its construction or assembly. Of course, at the beginning of the design process, the desired system does not exist. In this context, a model of the anticipated system can be very useful. In view of the complexity of a design process, particularly when striving for an optimal design, it is useful to incorporate system modeling as a tool for design iteration.

Modeling and design can go hand in hand in an iterative manner. In the beginning, by having some information about the system (e.g., intended functions, performance specifications, past experience, and knowledge of related systems) and using the design objectives, it will be possible to develop a model of sufficient (low to moderate) detail and complexity. By analyzing and carrying out computer simulations of the model, it will be possible to generate useful information that will guide the design process (e.g., generation of a preliminary design). In this manner, design decisions can be made, and the model can be refined using the available (improved) design.

## Some examples of mechatronic systems

Today, mechatronic systems are commonly found in homes, offices, schools, shops, and of course, in industrial applications. Common mechatronic systems include:

- Domestic appliances, such as fridges and freezers, microwave ovens, washing machines, vacuum cleaners, dishwashers, cookers, mixers, blenders, stereos, televisions, telephones, lawn mowers, digital cameras, videos and CD players, camcorders, and many other similar modern devices;

- Domestic systems, such as air conditioning units, security systems, automatic gate control systems.

- Office equipment, such as laser printers, hard drive positioning systems, liquid crystal displays, tape drives scanners, photocopiers, fax machines, as well as another computer peripheral.

- Retail equipment, such as automatic labeling systems, bar-coding machines, and tills found in supermarkets.

- Banking systems, such as cash registers, and automatic teller machines.

- Manufacturing equipment, such as pick- and-place robots, welding robots, automated guided vehicles (AGVs), and other industrial robots.

- Aviation systems, such as flight control actuators, landing gear systems, and other aircraft subsystems.

## Automated Simulation

Mathematical models of dynamic physical systems have been made ever since the invention of differential equations. But until the development of powerful computers, there were severe limitations on the analysis of these models. Practically speaking, dynamic system behavior could generally be predicted only for low-order linear models that often were not very accurate representatives of real systems.

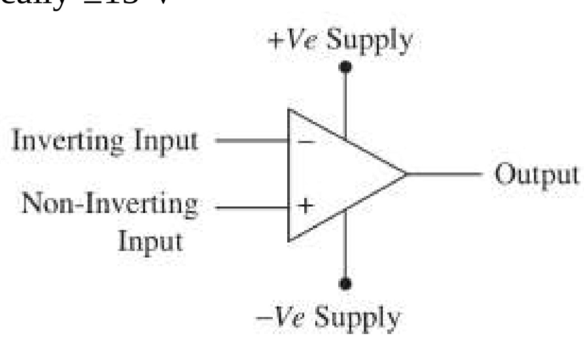
There is a lot to be said for the study of low-order linear models to gain an appreciation of system dynamics. However, computer simulation can now be used to gain experience with system dynamics even when the system models become large and when they contain nonlinear elements.

## Linear versus Nonlinear Control Systems

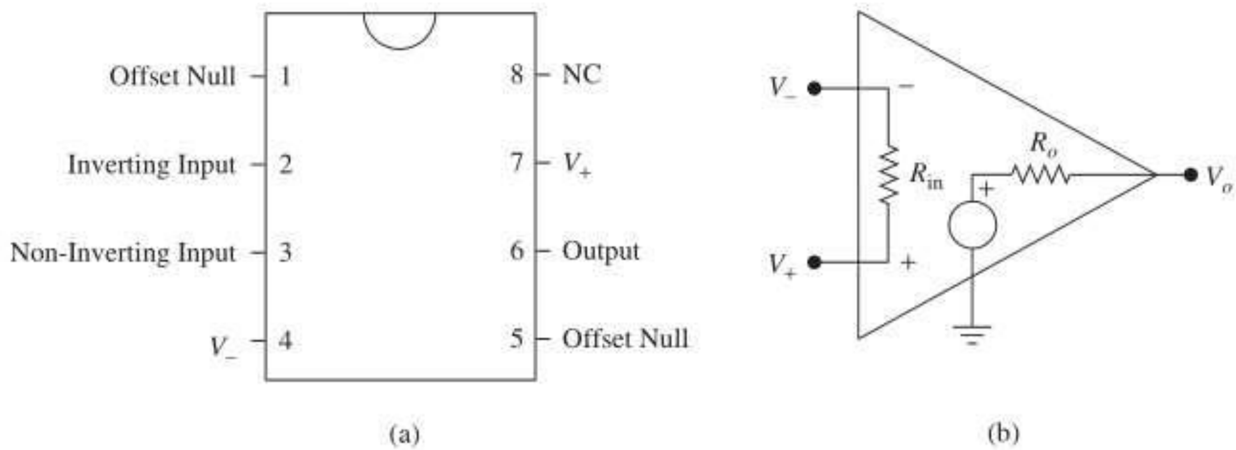
This classification is made according to the methods of analysis and design. Strictly speaking, linear systems do not exist in practice, because all physical systems are nonlinear to some extent. Linear feedback control systems are idealized models fabricated by the analyst purely for the simplicity of analysis and design.
For linear systems, a wealth of analytical and graphical techniques is available for design and analysis purposes. Nonlinear systems, on the other hand, are usually difficult to treat mathematically, and there are no general methods available for solving a wide class of nonlinear systems.

## Operational Amplifiers

Operational amplifiers (op-amps) are analog circuit components that require power to operate.
They are widely used in amplification and signal-conditioning circuits. The symbol for an op-amp is shown in Figure below. The symbol is a triangle, with two leads drawn on one side of the triangle, and the third lead is drawn at the apex opposite to that side. One lead is defined as the inverting input (-), the other lead is defined as the non-inverting input (+), and the third lead is the output. The voltages at these two inputs and at the op-amp output are referenced to the ground. The supply voltage is typically ±15 V

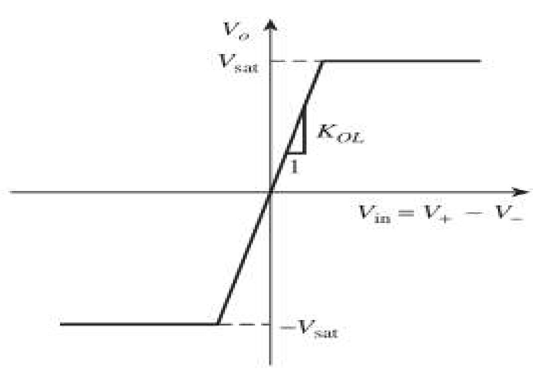


Commercially, op-amps are available in a variety of forms. A common form is the single op-amp in the form of an 8-pin integrated circuit (IC), an example of which is the LM741 chip from National Semiconductor.




(a) Pin layout for the LM741 and (b) model of an ideal op-amp

The inputs to the op-amp can be thought to be connected internally by a high-impedance resistor Rin. The value of this resistance is high enough (more than 1 M Ω), such that for ideal behavior, we can assume that no current flows between the V- and V+ input terminals. The output of the op-amp is modeled as a voltage source connected to a low impedance resistor Ro (less than 100 Ω ) in series. The voltage output is proportional to the difference between the input voltages, i.e.,



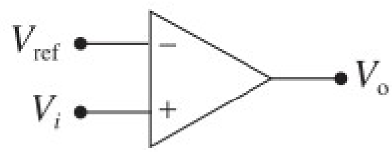

Open-loop input/ output relationship for an op-amp

Where KOL is the open-loop gain of the op-amp. The open-loop gain of the op-amp is usually very high (105 to 106), so a very small voltage difference between the two inputs results in a saturation of the output. For example, if the gain is 106, and the saturation voltage is 10 V, then the op-amp will saturate if the voltage difference between the input leads exceeds 10 V. Since the op-amp output is finite, but the op-amp has a very large gain, we assume that V+ = V-. The assumption that V+ = V- along with the assumption that no current flows into the input terminals are the two basic rules that are used to analyze ideal op-amp circuits. It should be noted that the saturation voltage of an op-amp is a function of the supply voltage for the op-amp and it is slightly smaller than it. For example, at supply voltage of 15 V, the saturation voltage is about 13 V. The open-loop input output relationship for an op-amp is shown in Figure above. In most cases, however, op-amps are not used in open-loop configuration but are used with a feedback loop between the output voltage lead and the inverting input lead. The closed-loop gain is much smaller than the open-loop gain, but the feedback provides more stable operating characteristics. Op-amps can perform various operations such as comparison, amplification, inversion, summation, integration, differentiation, or filtering.

## Comparator Op-Amp

A comparator is used to compare two voltage signals and switch the output to +Vsat if one of the signals is larger than the other, and to -Vsat otherwise, where Vsat is the saturated output of the op-amp. The circuit for an op-amp operating as a comparator is shown in Figure below. Here the op-amp is operating in open-loop, which means there is no feedback from the op-amp output to the input. The input voltage Vi is connected to the non-inverting input (+), and the reference voltage Vref is connected to the inverting input (-). The comparator output Vo is then:

$$V_o = \begin{cases} V_{sat}, & V_i > V_{ref} \\ -V_{sat}, & V_i < V_{ref} \end{cases}$$




Comparator op-amp circuit

A comparator can be used, as an example, in situations where it is needed to set an output on if a sensor input exceeds a certain value.

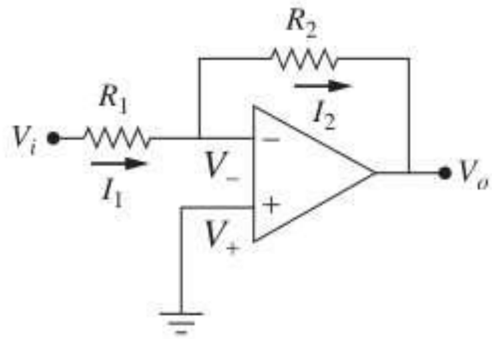
## Inverting Op-Amp

The inverting op-amp circuit is shown in Figure below which has a feedback loop between the op-amp output and the inverting input (-). An input voltage Vi is applied to the inverting input through a resistor R1, and the non-inverting input (+) is grounded. Since the non-inverting input is connected to ground,

$$V+ = V- = 0$$

The current I1 is equal to I2 because virtually no current flows between the inverting and the non-inverting inputs. The current I1 is equal to:

$$I_1 = \frac{V_i - V_-}{R_1} = \frac{V_i}{R_1}$$




and the current $I_2$ is equal to

$$I_2 = \frac{V_- - V_o}{R_2} = -\frac{V_o}{R_2}$$

Equating $I_1$ to $I_2$, and solving for the op-amp output $V_o$ gives

$$V_o = -\frac{R_2}{R_1} V_i$$

Thus, in this circuit the op-amp inverts the input voltage and amplifies it by a factor equal to the ratio of the resistance of R2 to R1. An application of this circuit is to perform signal inversion where the output will have a 180° phase shift with the input. Example below illustrates the use of the inverting op-amp circuit.

## Summing Circuit

Draw a circuit that shows how op-amps can be used to perform summation of three analog voltage signals.

**Solution:**

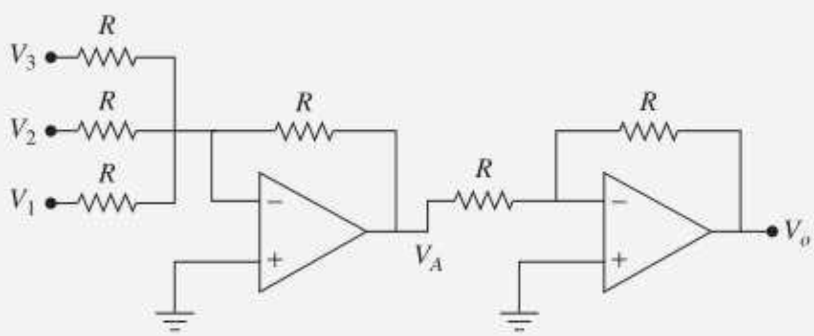



**Figure 2.29**

The circuit that performs this operation is shown in Figure 2.29. It basically consists of two cascaded op-amps each wired as an inverting amplifier. The three voltage signals are connected to the left op-amp. Note that the sum of the currents through the three resistors that are connected to the input voltages $V_1$, $V_2$, and $V_3$ is the same as the current that goes through the resistor in the feedback loop in the left op-amp circuit:

$$\frac{V_1 - V_-}{R} + \frac{V_2 - V_-}{R} + \frac{V_3 - V_-}{R} = \frac{V_- - V_A}{R} \quad (1)$$

Since $V_- = 0$, and cancelling $R$ from each term in Equation (1), this gives

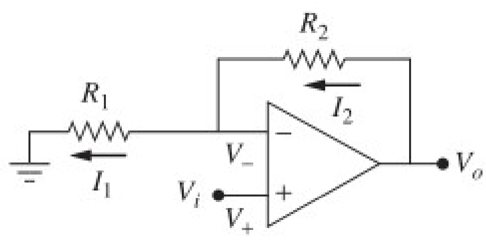
$$V_A = -(V_1 + V_2 + V_3) \quad (2)$$

From the second op-amp circuit, we get

$$V_o = -V_A = V_1 + V_2 + V_3 \quad (3)$$

## Non-Inverting Op-Amp

The non-inverting op-amp circuit is shown in Figure below. Here the non-inverting input (+) is connected to an input voltage Vi, and the inverting input (-) is connected to ground through a resistor R1. There is also a feedback loop between the op-amp output and the inverting input.




Non-Inverting op-amp circuit

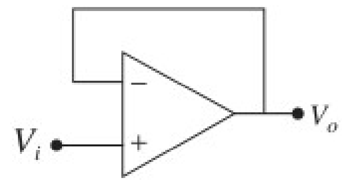
The voltage V+ is equal to V- and is also equal to Vi in this case. But the voltage at the inverting input is also given by

$$V_- = \frac{R_1}{R_1 + R_2} V_o$$

Since R1 and R2 act as a voltage-dividing circuit between Vo and ground. Thus, the output Vo of the op-amp is given by

$$V_o = \frac{R_1 + R_2}{R_1} V_i = \left(1 + \frac{R_2}{R_1}\right) V_i$$

Notice how the gain of the op-amp in this case is always greater than 1. Now if we let R2 to be zero and R1 to be infinite, this gives the circuit shown in Figure below. This circuit is known as a voltage follower or buffer, and in this case.

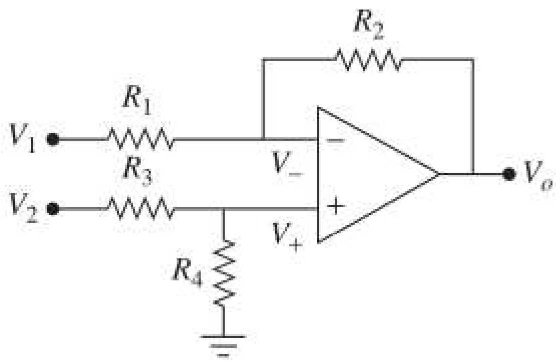



Voltage follower

Because the op-amp has a low output impedance (about 75 Ω ), and a high input impedance (about 2 MΩ ), the voltage follower circuit can be used in a variety of ways to reduce loading effects. The output of a voltage source can be connected to the buffer input to isolate the source from the rest of the circuit, or the buffer output can be connected to a high-impedance circuit. Note that in both the inverting and the non-inverting op-amp circuits shown above, the feedback between the output voltage and the inverting input is known as negative feedback. Negative feedback results in a linear relationship between the output and input voltages.

## Differential Op-Amp

An op-amp circuit with two voltages (V1 and V2) applied to its inputs is shown in Figure below. Two inputs (differential input) are used to reduce the circuit sensitivity to noise, since any noise applied to the circuit will be most probably the same on each of the inputs.




Differential input op-amp circuit

For this circuit, the current through the $R_1$ and the $R_2$ resistors is the same, since no current goes through the inverting input. This current is given by

$$I_{R_1} = \frac{V_1 - V_-}{R_1} = I_{R_2} = \frac{V_- - V_o}{R_2} \tag{2.45}$$

The voltage at the non-inverting input $V_+$ is given by

$$V_+ = \frac{R_4}{R_3 + R_4} V_2 \tag{2.46}$$

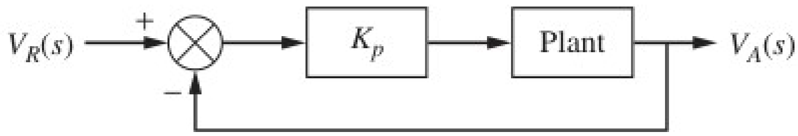
But $V_+ = V_-$. Substituting the expression for $V_+$ in Equation (2.45) and solving for $V_o$ gives

$$V_o = \frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right)V_2 - \frac{R_2}{R_1} V_1 \tag{2.47}$$

If $R_3 = R_1$ and $R_4 = R_2$, this expression simplifies to

$$V_o = \frac{R_2}{R_1}(V_2 - V_1) \tag{2.48}$$

and shows that the output of this op-amp circuit is proportional to the voltage difference between the inputs V2 and V1. A differential amplifier circuit can be used, for example, to implement an analog proportional control feedback loop.



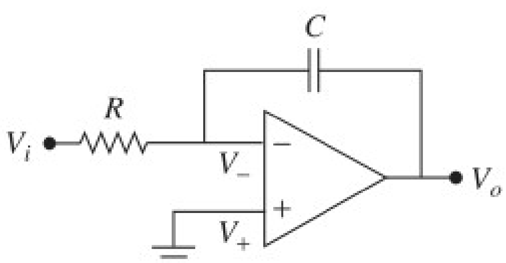

If the reference signal VR is the V2 voltage, the actual or measured signal VA is the V1 voltage, and the ratio is the proportional gain Kp, then the output of the differential amplifier will be

$$V_o = K_P(V_R - V_A)$$

Another application of the differential amplifier circuit is to amplify the difference between the voltages outputs from the arms of a Wheatstone bridge used to measure strain

## Integrating Op-Amp

The circuit for an integrating op-amp is shown in Figure below, which has a capacitor C in the feedback loop




Integrating op-amp circuit

Integrating op-amp circuit

$$I_C = C\frac{dV}{dt}$$

For this capacitor, V = V_ - V0, since V_ = 0. But the current through this capacitor is the same as the current that passes through the resistor R since no current flows through V_. This current is given by:

$$I_R = \frac{V_i - V_-}{R} = \frac{V_i}{R}$$

Thus,

$$\frac{dV_o}{dt} = -\frac{V_i}{RC}$$

Integrating above Equation from time t = 0 to time t = t1 gives:

$$V_o(t) = -\frac{1}{RC}\int_0^{t_1} V_i(t)\,dt + V_o(0)$$

where Vo(0) is the initial condition for the capacitor voltage. Thus, in this circuit, the op-amp produces an inverted output of the integral of the applied input voltage. Note that if the capacitor and the resistor were interchanged in this circuit, the op-amp will act as a differentiator of the input signal. The op-amp output in this case will be:

$$V_o = -RC\frac{dV_i(t)}{dt}$$

Problems

Q.1 what do you understand by the term ‘mechatronics’?
Q.2 what are the key elements of mechatronics?
Q.3 is mechatronics the same as electronic engineering plus mechanical engineering?
Q.4 is mechatronics as established as electronic or mechanical engineering?
Q.5 List some mechatronic systems that you see every day.