Tishk International University – Mechatronics Department

# Digital Control Systems
# (ME 412)

**Lecture (1)**

# Digital Control Systems: An Introduction

**Prof. Qasim M. Obaidi**
TIU, Erbil, Iraq

# **Course Title:** Mechatronics Instrumentation

- **Instructor:** Prof. Qasim M. Obaidi.
- **Email:** *qasim.obaidi@tiu.edu.iq*
- **Semester:** First, 2024-2025
- **Time:** (9:00-12:00) Tuesday.
- **Office Hours:** (9:00-12:00) Sunday & Wednesday.
- Appointments to discuss the course should be made by email.
- **Course Material:** http://www.tiu.edu.iq/academics/kaubaidy/page.php?id=7

## Course Description:

The Digital Control Systems course focuses on the principles and techniques used in the design and implementation of digitally operated control systems. This course covers the transition from traditional analogue to digital control methods, the design of digital controllers and the stability analysis of digital systems, with an emphasis on the use of discrete-time signals and systems. .

- **Primarily through:**
  - **Lectures:** 45 hours/semester, 3 hours/week.
  - **Assignments:** 2 assignments for each student.
  - **Homework:** 2 homework for each student.
  - **Project:** Project for each student

  » We will also discuss student projects.

## Intended Learning Outcomes:

Upon completion of this course, students will be able to:

- Understanding the fundamental concepts of digital control systems, including discrete-time signal processing and system analysis.
- Analyze the behavior and stability of discrete-time systems using tools such as Z-transforms and difference equations techniques.
- Design and implement digital controllers, including proportional-integral-derivative (PID) controllers.
- Understand the effects of sampling and quantization on system performance.
- Use simulation tools to model, simulate, and test digital control systems.

## Prerequisites:

- Students are expected to be familiar with electronic circuits, control systems, systems modeling and simulation techniques, systems design and implementation.

- Some basic familiarity with digital electronics, microprocessors interfacing and artificial intelligence.

## Grades:

| | |
|---|---|
| • Quizzes: | 10% |
| • Assignments, Homework & Projects: | 20%, |
| • Mid Exam: | 30% |
| • Final Exam: | 40% |

## Projects:

- Define your own project and write a proposal.
- Requires pilot investigation of the project (simulation and/or prototype) with submission of a final report.
- Final report contents: Project title, Objective, Introduction, Hardware design, Software design, Conclusion, References.
- Team projects are permitted (if required), but prior approval must be taken with specifying the tasks of each group member!

# Timetable:

| Week | Basic and support material to be covered | HW/Project |
|---|---|---|
| 1 | Introduction to digital control; Analog & Digital control; Why digital control? | |
| 2 | Discrete-Time Systems; Analog systems with piece wise constant inputs. | |
| 3 | Discrete-Time Systems; Difference equations. | |
| 4 | The z-transform; Properties of the z-transform. | HW1 |
| 5 | Inversion of the z-transform; The final value theorem. | Assignment1 |
| 6 | Pulse transfer function: Open-loop and closed loop. | |
| 7 | The time response of a discrete-time system. | |
| 8 | The sampling theorem; Selection of the sampling frequency. | |
| 9 | Modeling of Digital Control Systems; ADC model, DAC model, The transfer function of the ZOH. | HW2 |
| 10 | The closed-loop transfer function. | Assignment1 |
| 11 | Stability of Digital Control Systems, Definitions of stability. | |
| 12 | Stable z-domain pole locations, Stability conditions, Stability determination. | |
| 13 | Digital Control System Design; z-Domain root locus. | Project |
| 14 | z-Domain digital control system design. | |
| 15 | PID control design in the z-domain. | |

# Textbook:

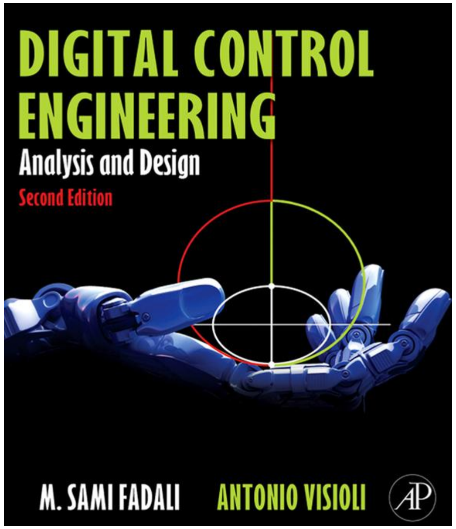
Title: Digital Control Engineering Analysis and Design.

By: M. Sami Fadali, and Antonio Visioli,

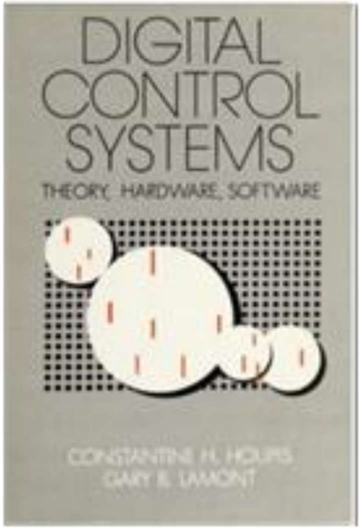
Publisher: Academic Press, Elsevier, 2[nd] Edition, 2013.

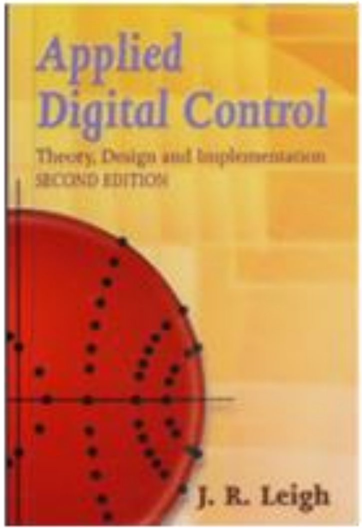
ISBN: 978-0-12-394391-0.

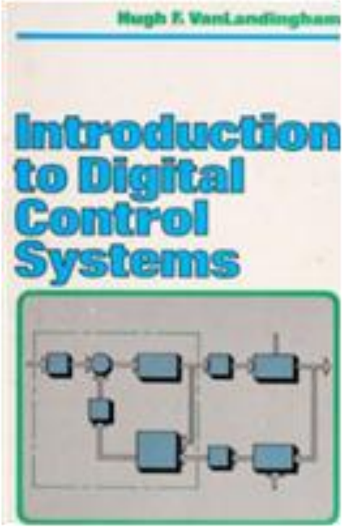
https://www.sciencedirect.com/book/9780128144336/digital-control-engineering#book-info

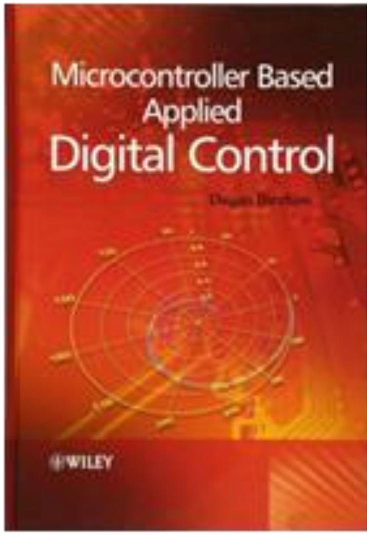



# Reference Books:

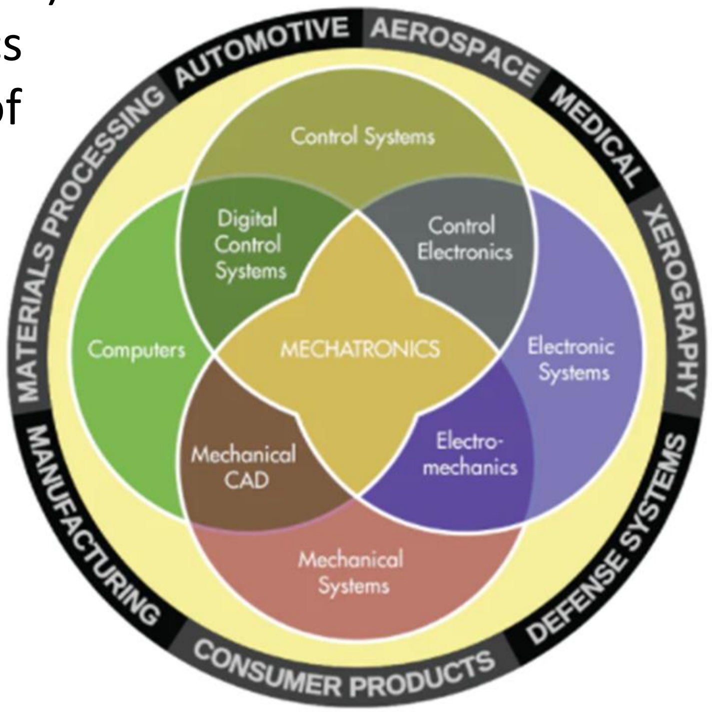



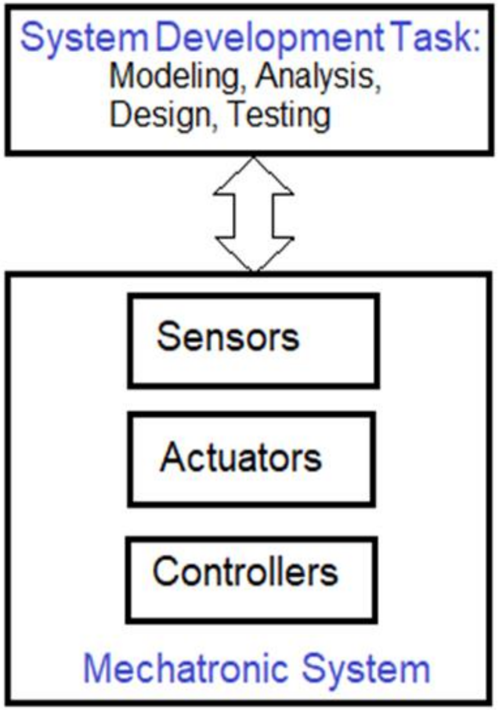
# What is Mechatronics?

- Mechatronics is a concept of Japanese origin (1980's) and can be defined as the application of electronics and computer technology to control the motions of mechanical systems.
- It is a multidisciplinary approach to product and manufacturing system design.
- It involves application of electrical, mechanical, control and computer engineering to develop products, processes and systems with greater flexibility, ease in redesign and ability of reprogramming.  It concurrently includes all these disciplines.
- Mechatronics can also be termed as replacement of mechanics with electronics or enhance mechanics with electronics.



## Concept of Mechatronics System:

The main concept of Mechatronics is to work smart and achieve huge results in a short time.




**Impact of Controllers:**

With the help of electronics and sensor technology, mechatronics systems are providing high levels of precision and reliability.

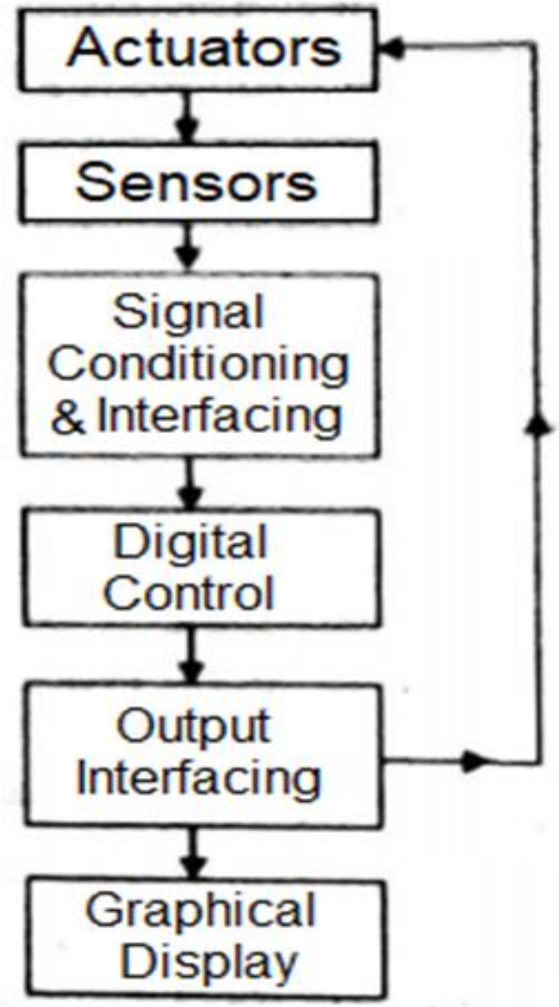
**Impact of Technology:**

Through the use of new technology (IoT, AI & MCs), it is now easy to add new functions and capabilities to a product or system.

Many mechatronics applications (such as automobiles, home washing machines, medical devices) have become “smart” today, equipped with digital control systems and safety protection devices. Digital controllers play an important role in mechatronics systems.

# Components of Mechatronics system:

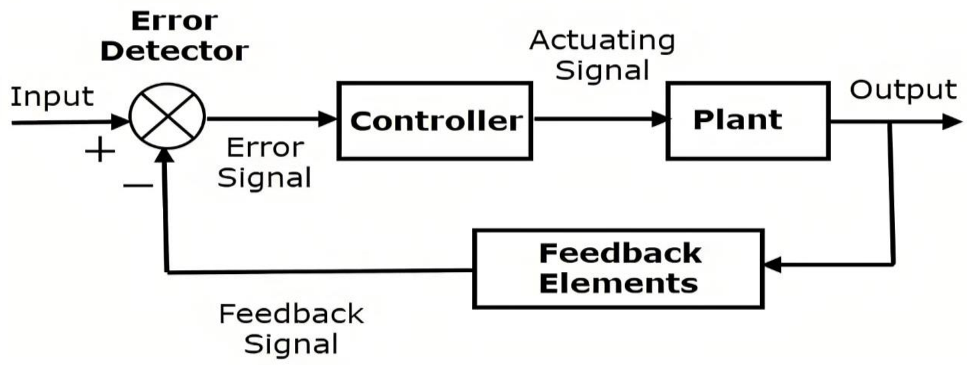
The term mechatronic system includes a number of devices and systems. Microcontrollers are included in these devices, providing more flexibility and control capabilities in the system design.




- **Actuators:** produce motion or cause some action.
- **Sensors:** detect the state of the system parameters, inputs and outputs.
- **Input/output signal conditioning and interfacing:** provide connection between the control system circuits and the input/output devices.
- **Digital controllers:** Digital controllers are implemented within mechatronics systems to improve operating conditions (optimality, accuracy and reliability).
- **Graphic display:** provide visual feedback to users.

# Control System Design:

To understand mechatronics systems, mathematical models of these systems must be obtained. Since mechatronics are dynamic systems, the descriptive equations are usually differential equations. If these equations can be linearized, the Laplace transform can be used to simplify the solution method.



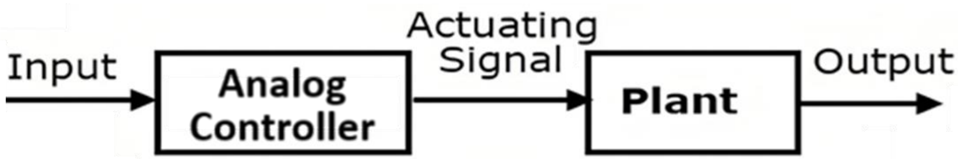

**Steps:**

1. Define the system and its components.
2. Formulate the mathematical model based on the basic principles.
3. Obtain the differential equations that represent the mathematical model.
4. Solve the equations for the desired resulting variables.
5. Check the solutions and assumptions.
6. If necessary, redesign the system control unit.

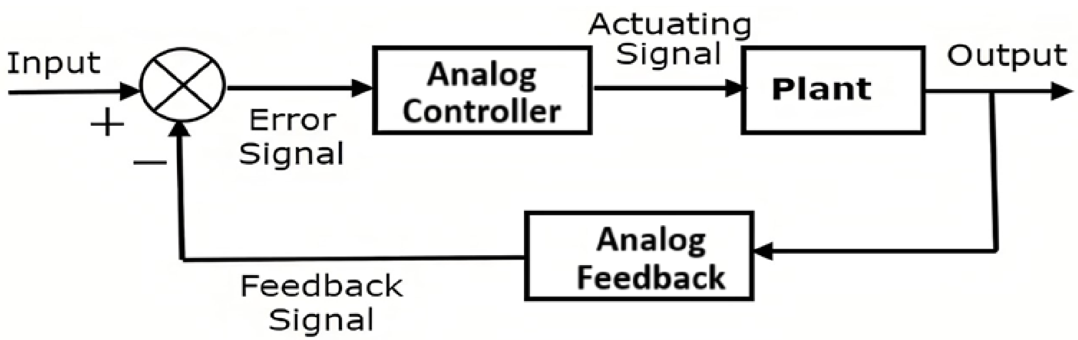
## Classification of Control Systems:

### 1. Open Loop and Closed Loop Control Systems:

- In open loop control systems, output is not fed-back to the input. So, the control action is independent of the desired output.



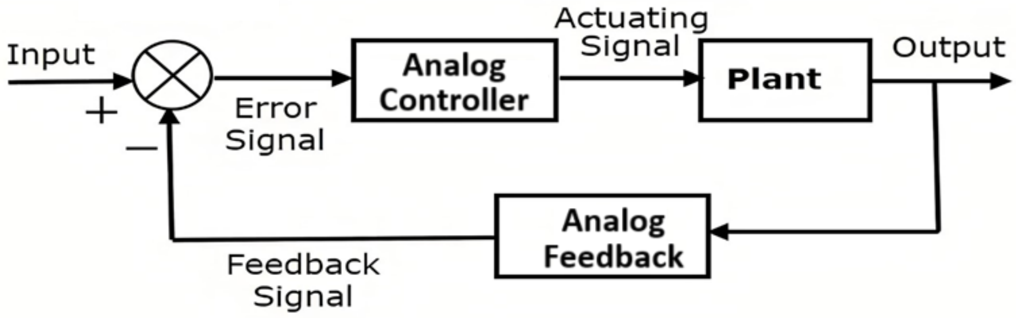

- In closed loop control systems, output is fed back to the input. So, the control action is dependent on the desired output.



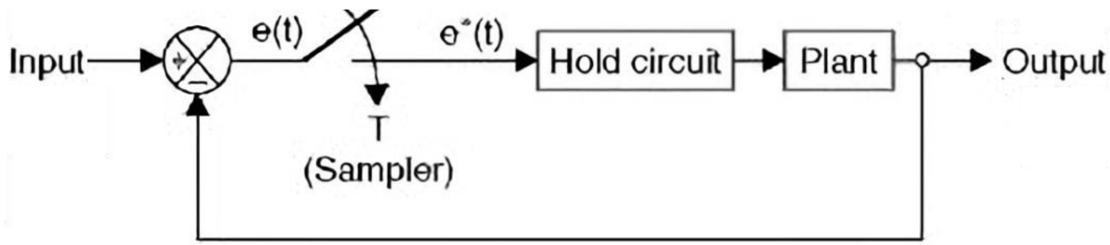
## Classification of Control Systems:

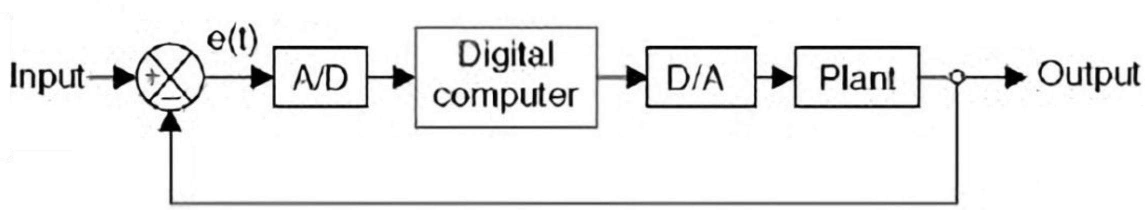
## 2. Continuous time and Discrete-time Control Systems:

- In continuous time control systems, all the signals are continuous in time.




- In discrete time control systems, there exists one or more discrete time signals.

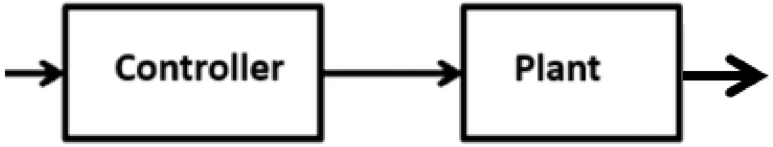


## Classification of Control Systems:

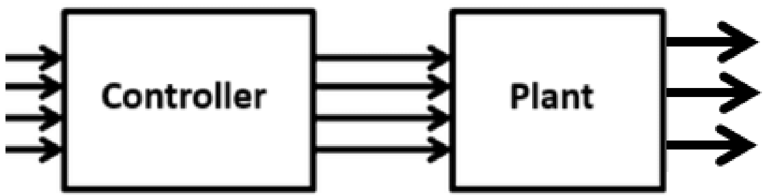
### 3. SISO and MIMO Control Systems:

- Single Input and Single Output (SISO) control systems have one input and one output.



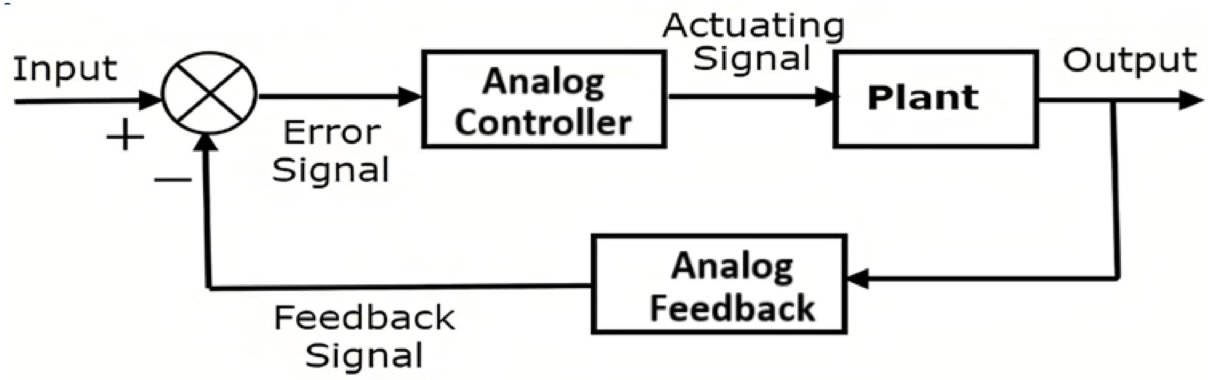

SISO System

- Multiple Inputs and Multiple Outputs (MIMO) control systems have more than one input and more than one output.




MIMO System

# Analog Control Systems

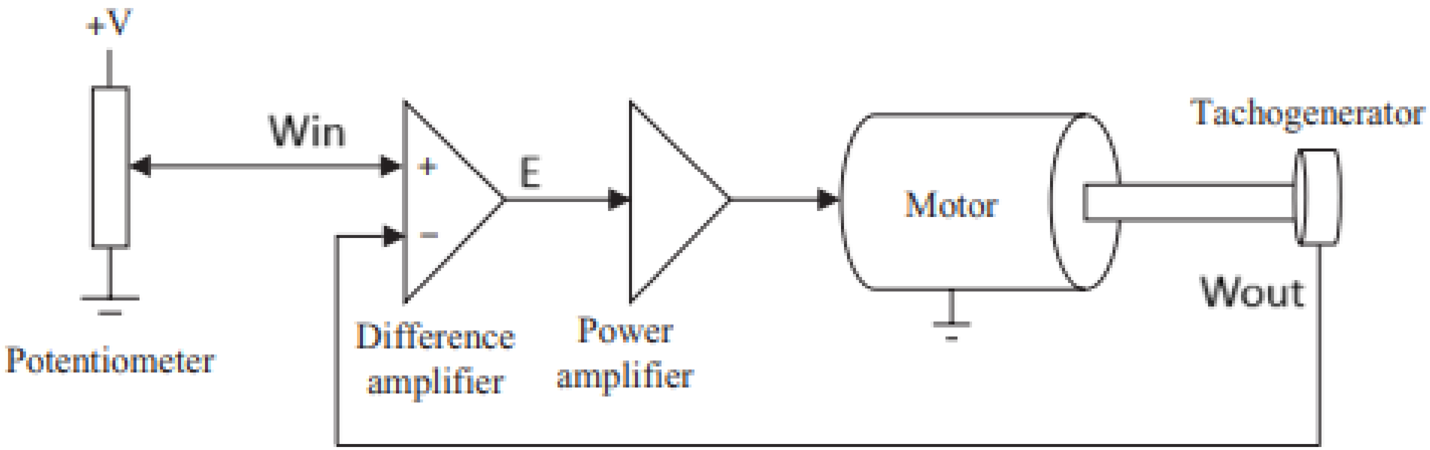



They are simple and work with continuous signals.

- ✓ **Continuous signals:** Analog systems operate with continuous signals such as voltage or current that change over time.
- ✓ **Real-time processing:** Process information in real time, allowing for immediate responses to changes in system behavior.
- ✓ **Simplicity:** Many analog systems are simpler to design and implement because the controllers used are simple.
- ✓ **Linear & nonlinear behavior:** They can model linear and nonlinear system dynamics.
- ✓ **Stability:** Analog systems can be designed to be inherently stable, especially when feedback loops are used to maintain desired performance.
- ✓ **Low latency:** Because there is no need to convert from analog to digital, these systems often have lower latency, which is critical for applications that require immediate action.
- ✓ **Controller parameter tuning:** Controller parameters in analog controllers (such as PID controllers) can be adjusted manually or using hardware components.

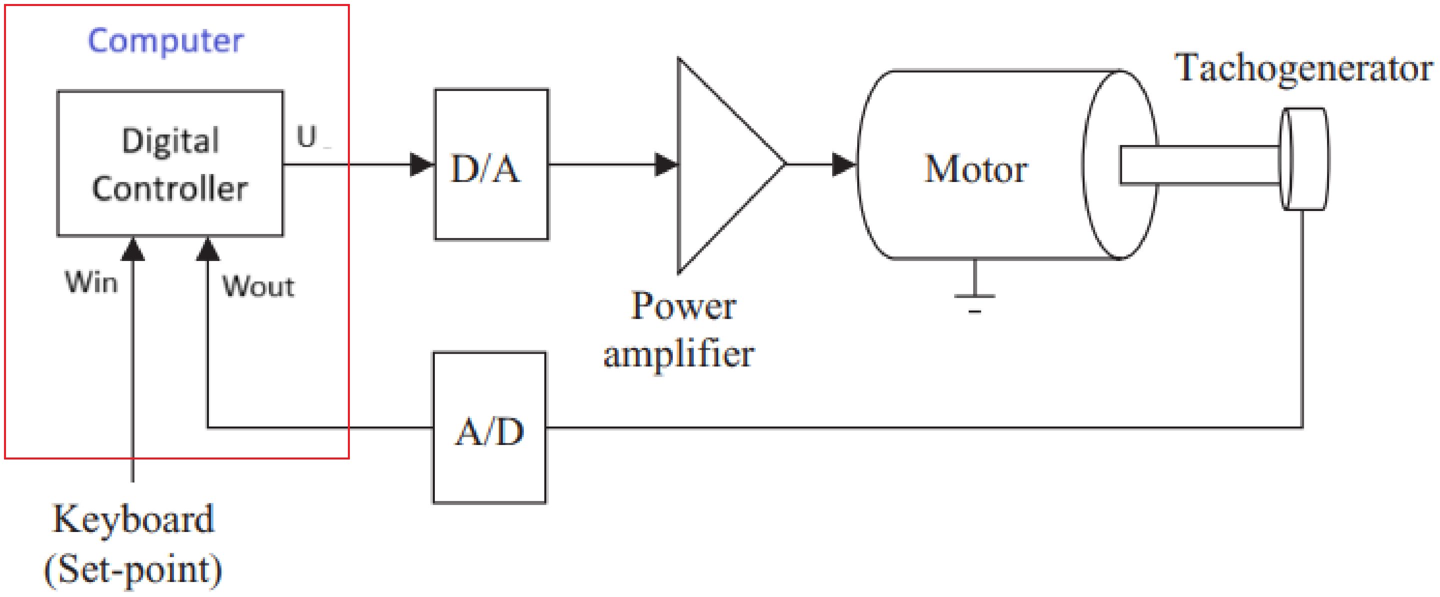
## Example: Analog Controller

A typical closed-loop analog speed control system sets the desired motor speed (Win) using a potentiometer. A tacho-generator generates a voltage proportional to the motor's speed (Wout), which is subtracted from the desired speed to produce the error signal (E). Based on this error signal, the power amplifier drives the motor to achieve the desired speed. The motor will maintain this speed as long as the error signal remains zero.



## Digital Control System:

The desired speed (Win) is entered from the keyboard into the digital controller. The controller also receives an output signal representing the motor speed (Wout) through a A/D converter.  The error signal (E) is calculated by subtracting the tacho-generator reading from the desired speed. A D/A converter then converts this signal into analog form, which is fed to the power amplifier. The power amplifier subsequently drives the motor.

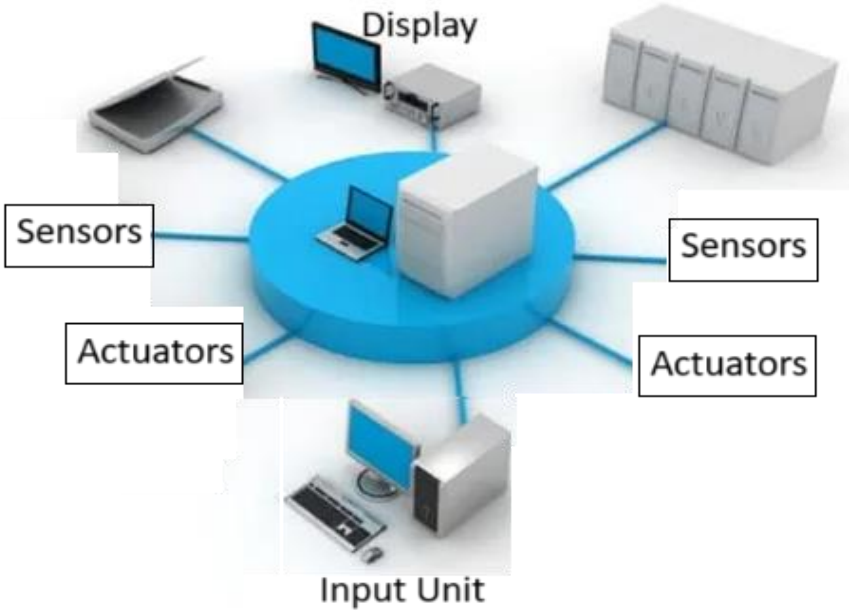


# Centralized and Distributed Control Systems:

## 1. Centralized Control System:

- Until the beginning of 1980s, computer control was strictly centralized.
- A single large computer was used to control the plant.
- All sensors, actuators, input units and output units must be connected directly to this central computer.

- The advantages of CCS are as follows:
  - ✓ It is easy to manage the computer.
  - ✓ Only one computer is used.
  - ✓ Less number of people are required.
  - ✓ The controller algorithm is implemented in a single central computer.

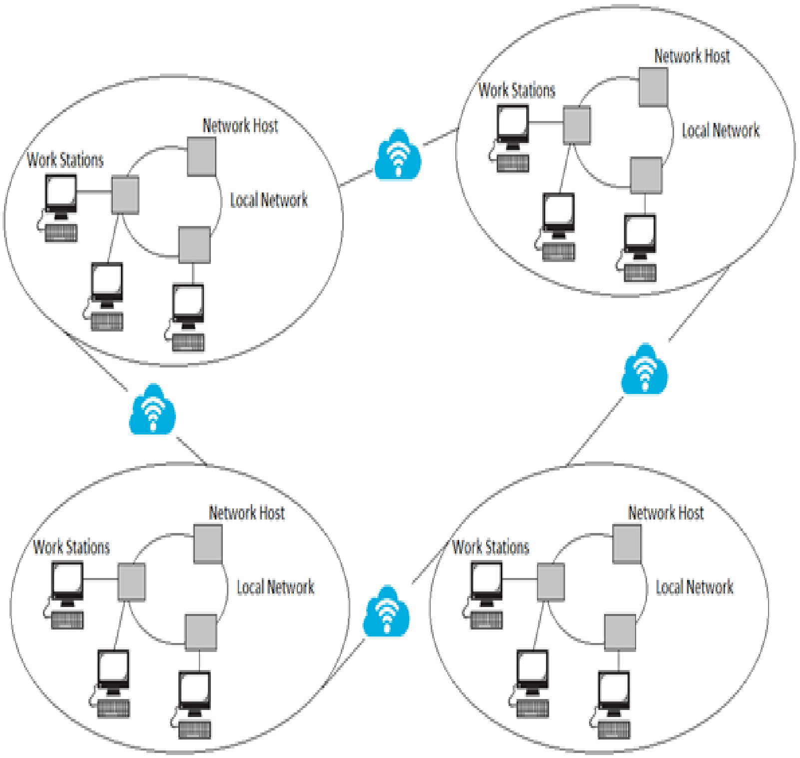


## 2. Distributed Control System (DCS):

- Today, DCSs are widely used due to the significant decline in computer costs and the availability of computer networks.
- A DCS consists of multiple computers installed at different locations, each performing independent control operations.
- Sensors and actuators can be connected to local computers that implement local control algorithms. Local computers in a distributed control environment are used for direct digital control.

The main advantages of DCSs include:

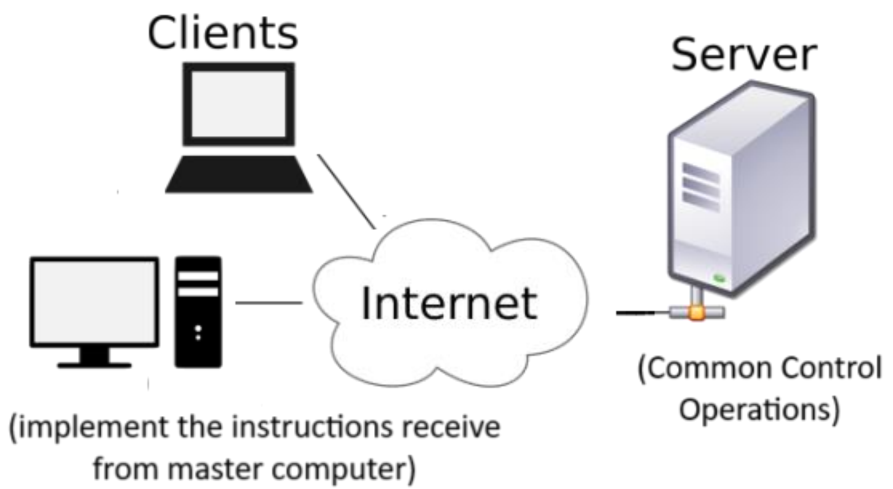
1. DCSs offer better performance compared to CCSs.
2. In a CCS, if one computer fails, the entire plant may become unusable. While, if a computer fails in a DCS, only a small part of the plant is affected, and the workload of the failed computer can usually be redistributed among other computers.
3. DCSs can be easily expanded by adding more computers to the network.
4. DCSs can be easily modified to meet the specific requirements of the plant.



# Direct Digital Control (DDC):

In a DDC application the computer is used to carry out the control action for the plant. It is also possible to add some level of supervisory control action to a DDC computer, such as displaying the values of sensors, inputs and outputs.
DCSs are used as client–server systems. In such a system one computer is designated as the server and carries out the common control operations. Other computers in the system are called clients and they obey and implement the instructions they receive from the master computer.

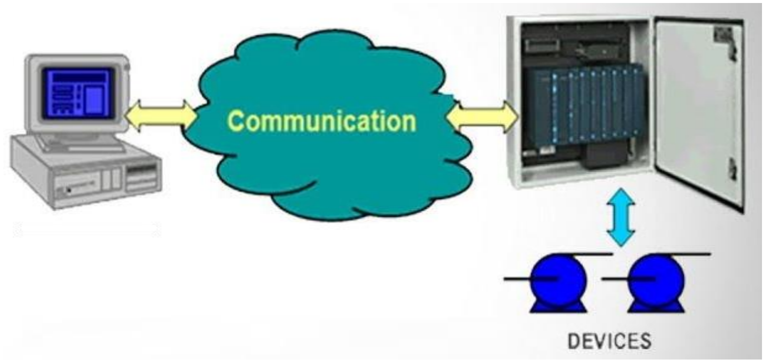
**For example:** The task of a client computer could be to receive and format analog data from a sensor, and then pass this data to the server computer every second.



# SCADA SYSTEMS:

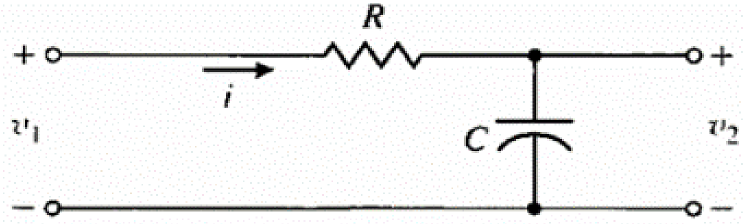
The term SCADA stands for Supervisory Control and Data Acquisition. SCADA systems integrate data acquisition with system monitoring and control activities using graphical software packages.

- SCADA systems consist of both hardware and software, typically implemented using PCs. Common hardware components include the computer, keyboard, touch screen, sensors, and actuators. The software is presented through a graphical user interface, allowing users to view parts of the plant, sensor data, and actuator data, all displayed in colored screen.
- In a SCADA system, users can access a graphical interface to monitor or adjust settings within the plant. SCADA systems can be developed using popular visual programming languages such as Visual C++ or Visual Basic.
- One key advantage of a SCADA system is that it enables users to easily monitor the overall status of the system. It is crucial for a SCADA system to be secure and password-protected to prevent unauthorized access to the control screens.



# Transfer Function of a Linear System:

## Example:




$$V_1(s) = \left(R + \frac{1}{Cs}\right)I(s), \quad V_2(s) = I(s)\left(\frac{1}{Cs}\right)$$

Then the transfer function is obtained as the ratio $V_2(s)/V_1(s)$,

$$G(s) = \frac{V_2(s)}{V_1(s)} = \frac{(1/Cs)}{R + 1/Cs} = \frac{1}{RCs + 1} = \frac{1}{\tau s + 1}$$

where $\tau = RC$, the **time constant** of the network.
The transfer function could be immediately obtained if one observes that the circuit is a voltage divider, where

$$\frac{V_2(s)}{V_1(s)} = \frac{Z_2(s)}{Z_1(s) + Z_2(s)},$$

and $Z_1(s) = R$, $Z_2 = 1/Cs$.

## Solution of Differential Equations:

### Example:

Consider a system represented by the differential equation,

$$\frac{d^2y}{dt^2} + 4\frac{dy}{dt} + 3y = 2r(t)$$

where the initial conditions are $y(0) = 1, \frac{dy}{dt}(0) = 0$, and $r(t) = 1, t \geq 0$.

The Laplace transform yields

$$[s^2Y(s) - sy(0)] + 4[sY(s) - y(0)] + 3Y(s) = 2R(s).$$

Since $R(s) = 1/s$ and $y(0) = 1$, we obtain

$$Y(s) = \frac{s + 4}{s^2 + 4s + 3} + \frac{2}{s(s^2 + 4s + 3)}$$

Then the partial fraction expansion yields

$$Y(s) = \left[\frac{3/2}{s + 1} + \frac{-1/2}{s + 3}\right] + \left[\frac{-1}{s + 1} + \frac{1/3}{s + 3}\right] + \frac{2/3}{s}$$

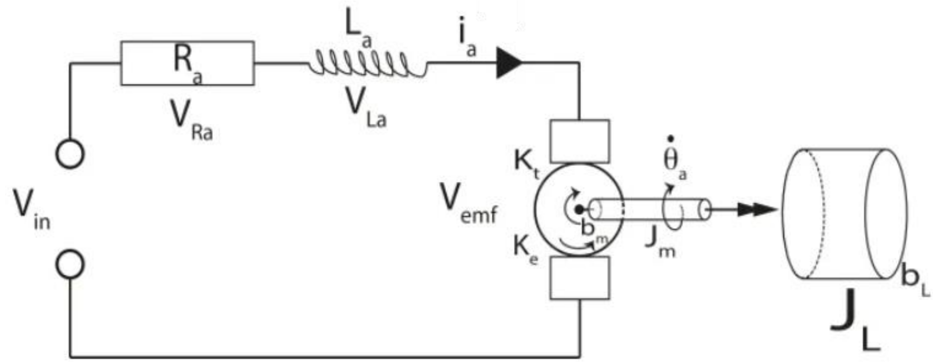
Hence, the response is

$$y(t) = \left[\frac{3}{2}e^{-t} - \frac{1}{2}e^{-3t}\right] + \left[-1e^{-t} + \frac{1}{3}e^{-3t}\right] + \frac{2}{3}$$

and the steady-state response is $\lim_{t\to\infty} y(t) = \frac{2}{3}$

# Example: Transfer function of the DC motor

A DC motor is a power drive device that delivers power to a load. A DC motor converts direct current (DC) electrical energy into rotational mechanical energy. A large portion of the torque generated in the rotor (armature) of the motor is available to drive an external load.




**Mechanical Characteristics:**

The air-gap flux Φ of the motor is proportional to the field current, so that

$$\phi = K_f i_f$$

The torque developed by the motor is assumed to be related linearly to and the armature current as follows:

$$T_m = K_1 \phi i_a(t) = K_1 K_f i_f(t) i_a(t)$$

For field current controlled motor (Ia is constant), the Laplace transform is,

$$T_m(s) = (K_1 K_f I_a) I_f(s) = K_m I_f(s)$$

The motor torque Tm(s) is equal to the torque delivered to the load (since Td is neglected);

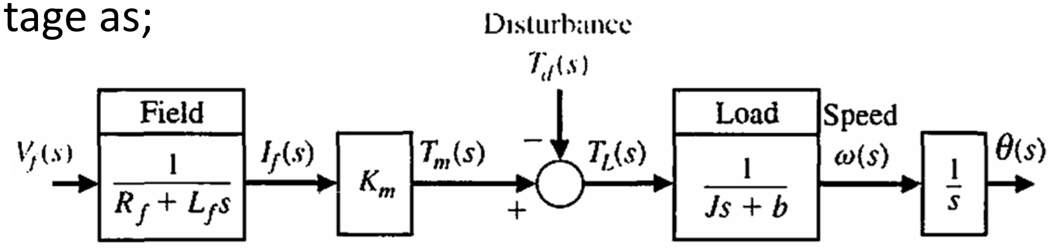
$$T_L(s) = Js^2\theta(s) + bs\theta(s) = T_m(s) = K_m I_f(s)$$

**Electrical characteristics:**

The field current is related to the field voltage as;

$$V_f(s) = (R_f + L_f s) I_f(s)$$

$$I_f(s) = \frac{V_f(s)}{R_f + L_f s}$$




The transfer function of the motor-load combination is;

$$G(s) = \frac{\theta(s)}{V_f(s)} = \frac{K_m}{s(Js + b)(L_f s + R_f)} = \frac{K_m/(JL_f)}{s(s + b/J)(s + R_f/L_f)}$$

The transfer function may be written in terms of the time constants of the motor as;

$$G(s) = \frac{\theta(s)}{V_f(s)} = \frac{K_m/(bR_f)}{s(\tau_f s + 1)(\tau_L s + 1)}$$

where $\tau_f = L_f/R_f$ and $\tau_L = J/b$.

Note: If $\tau_L > \tau_f$ the field time constant may be neglected.