HUMBER ENGINEERING

MENG 3510 – Control Systems
LECTURE 1

HUMBER

WE ARE HUMBER

LECTURE 1
Introduction to Control Systems

- What is Control Systems?
- Control Systems Configurations
  - Open-loop Control vs Closed-loop Control
- Basic Elements, Terminologies and Variables
- Control Systems Design Procedure
- Properties of Feedback Control Systems
- Review of Dynamic System Modeling

Control Systems

❑ What is a Control System?

- **Control System** is a set of devices/components to manage, command, or regulate the behavior of other systems to achieve the desired results.
    - Home Heating System
    - Road Traffic System
    - Industrial Robot
    - Laptop Cooling System
    - Manufacturing Process
    - Power Plant
    - Aircraft / Spacecraft Navigation System
    - Fuel Injection System in Automobile
    - Washing Machine
    - Stock Market
    - …………

Advantages of Control Systems

❑ Why do we need control system?

✓ **More Convenient**

- Intelligent laundry machine
- Emissions control system, …

✓ **More Efficient**

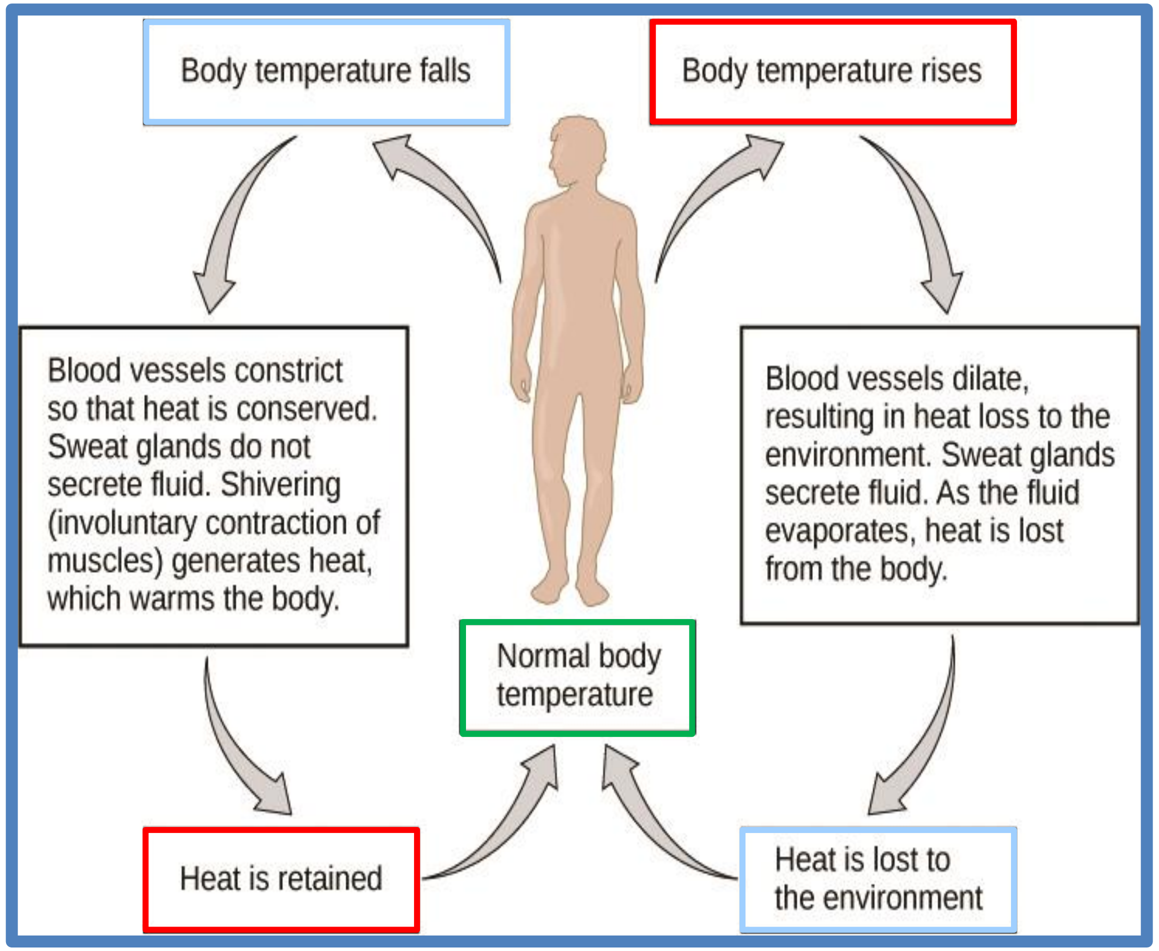
- Lower cost
- Save time, money and energy, …

✓ **Dangerous/Impossible Situations**

- Working in the Space
- Hot/cold places
- Nanometer scale precision positioning, …

✓ **Exist in Nature**

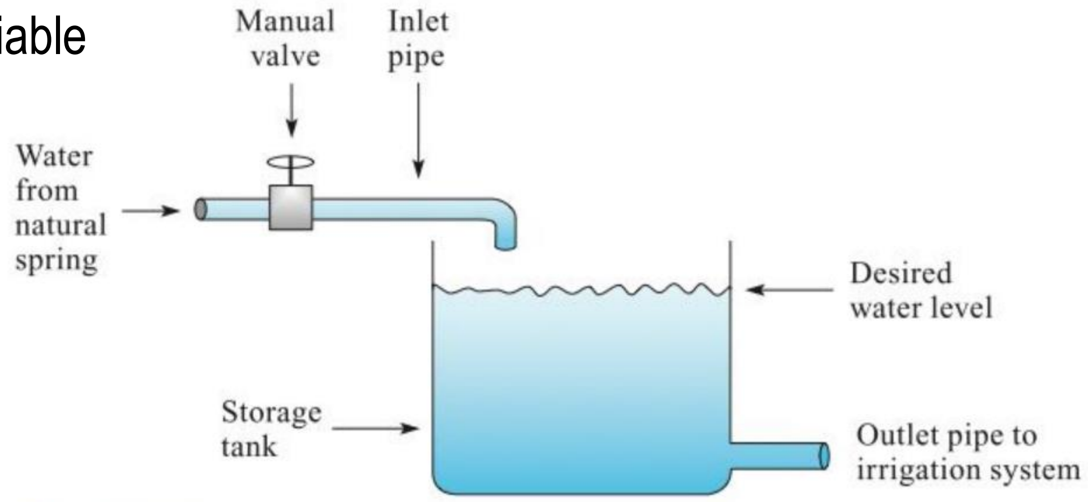
- Human body temperature control
- Heart rate control
- Blood insulin level control



Control Systems Configuration

- Control systems are classified based on ***how*** they control the variables, either **open-loop** or **closed-loop**.

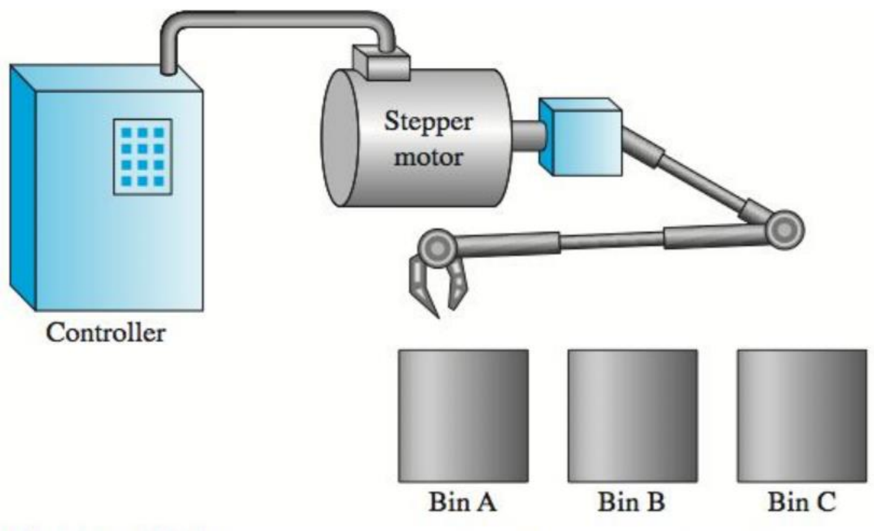
1) **Open-loop Control** is a control system without feedback measurement signal.
   - The system is controlled only by command input
   - Controller determines the control signal without any feedback from the controlled variable
   - Sensitive to disturbances and unreliable
   - The system cannot correct any errors that it could make
   - Required calibration and accurate modeling of the system
   - Human operator inspection may require
   - Low cost and simple in design and construction
   - Applicable for tasks that are predefined, repeatable, sequential, and not vary



An Open-loop Reservoir System to Store Water for an Irrigation System

Example

- Firing a bullet
- Shooting a basketball
- Microwave oven
- TV remote control
- Laundry machine
- Time based toaster
- ………….



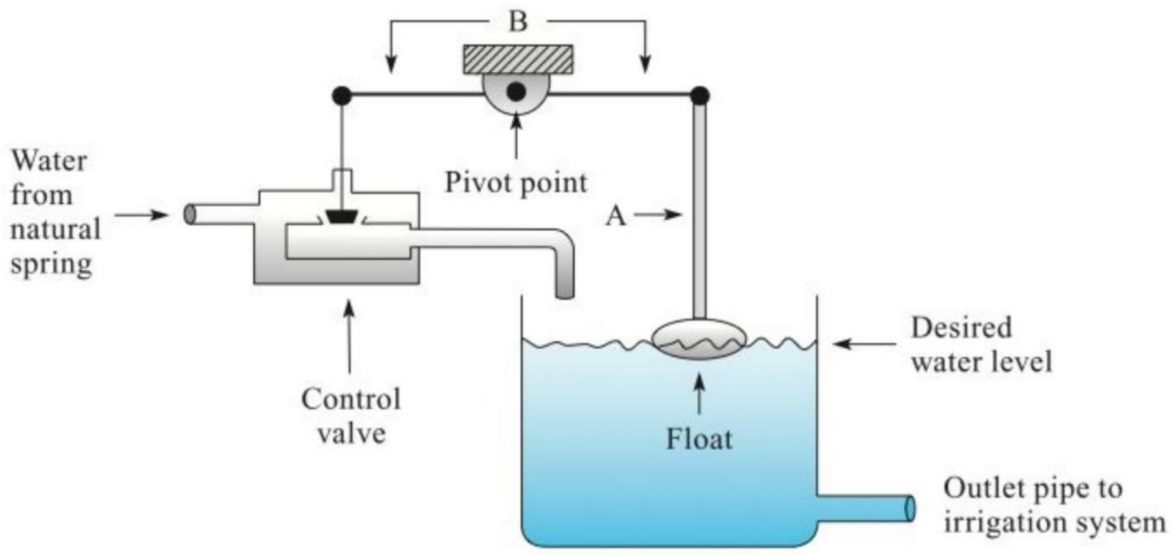
An Open-loop Pick-and-Place Application

Control Systems Configuration

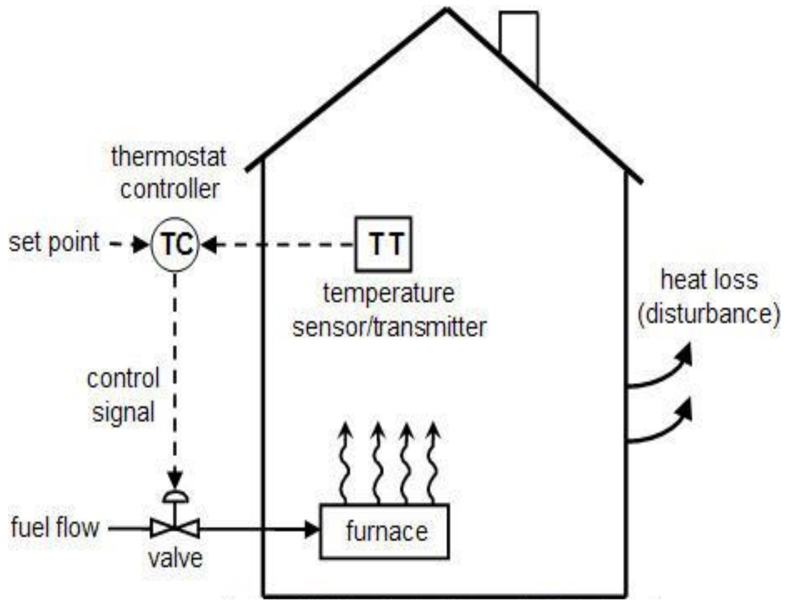
- Control systems are classified based on ***how*** they control the variables, either **open-loop** or **closed-loop**.

2) Closed-loop Control (Feedback Control) uses feedback measurements to regulate and control the system.

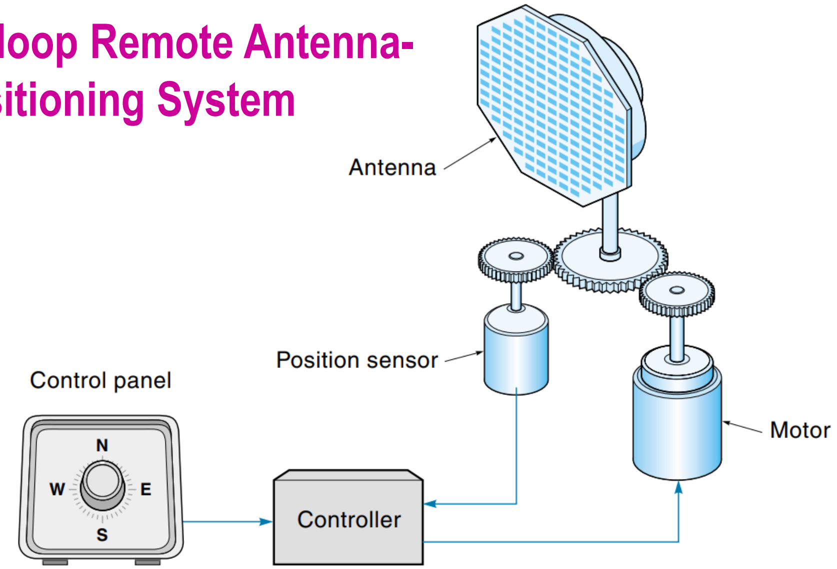
- Controller uses the controlled variable to help determine the control signal
- Compare actual behavior with desired behavior by using **feedback**, make corrections based on the error
- Less sensitive to the system parameters and robust to disturbances
- Provides self-regulating and tracking capability to the system
- Required sensor or measurement device, **additional hardware** and **cost**



A Closed-loop System that uses a Linkage Mechanism as a Feedback Device



A Closed-loop Home-heating System

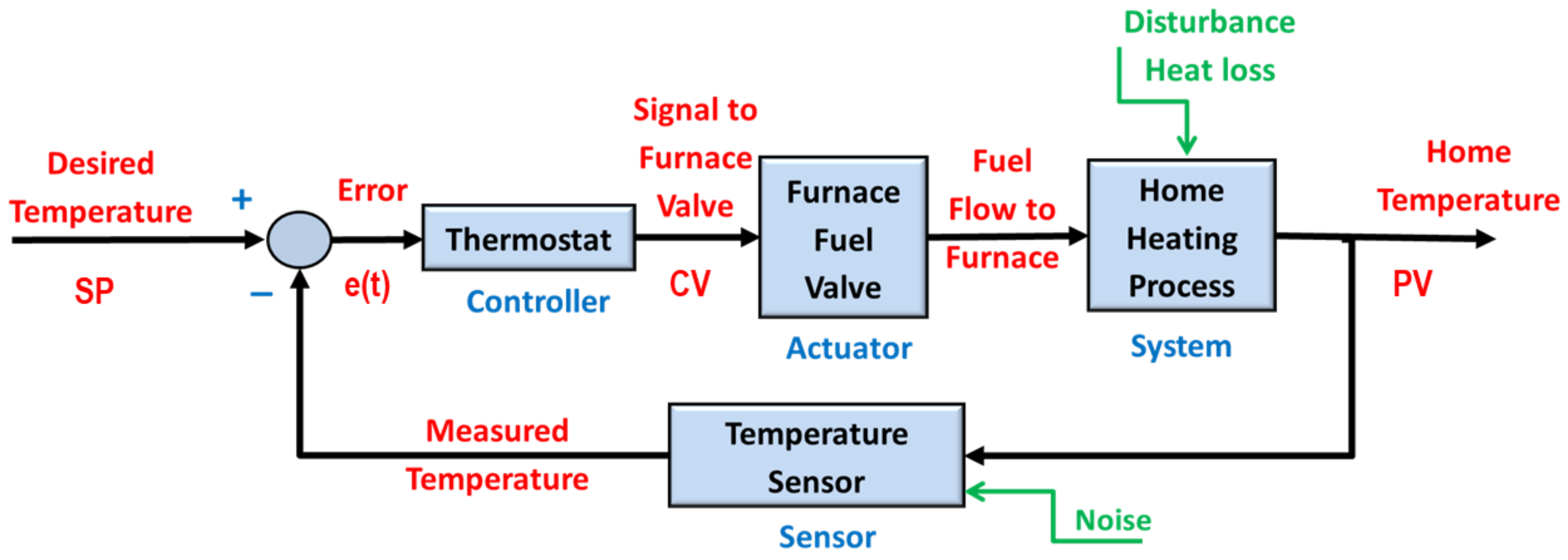


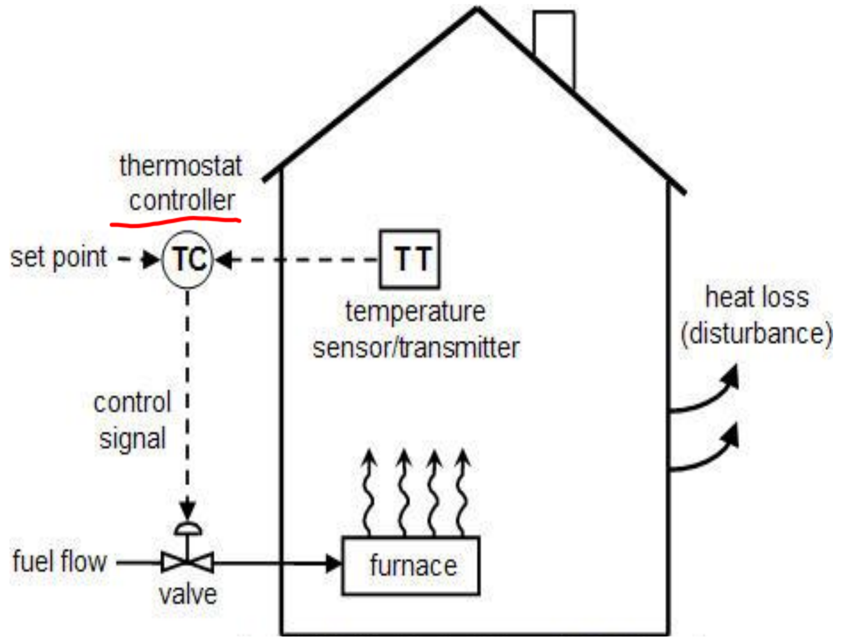
A Closed-loop Remote Antenna-Positioning System

Block Diagram Representation

- **Block diagram representation**, is usually used by control engineers to represent control systems because of its simplicity and versatility to show the interconnection of the system components.
- It provides a graphical approach to describe how components of a control system interact.
- The input–output relationship represents the cause-and-effect relationship of the process, which in turn represents a processing of the input signal to provide a desired output signal.

- Basic elements of block diagram representation
  - Rectangles → Subsystems and Elements
  - Arrows → Input and Output of subsystems and Signal flow directions
  - Circles → Comparators to add or subtract signals

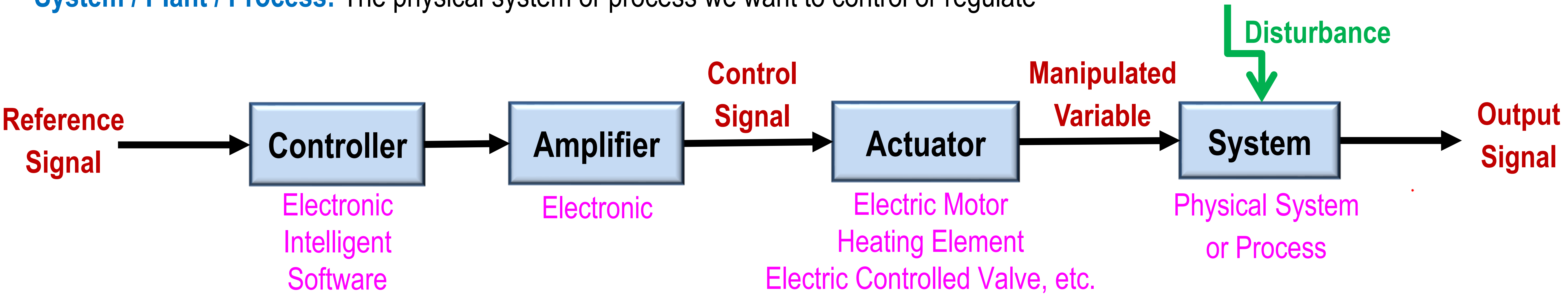




A Closed-loop Home-heating System

Basic Elements of an Open-loop Control System

- **Controller (The <u>brain</u>):** The device that we use it to control the system behavior
- **Amplifier:** The device receives signals from the controller and converts them into power sufficient for the actuator to drive the load.
- **Actuator (Final Control Element / The <u>muscle</u>):** The device that takes power and command from amplifier to derive the system.
- **System / Plant / Process:** The physical system or process we want to control or regulate

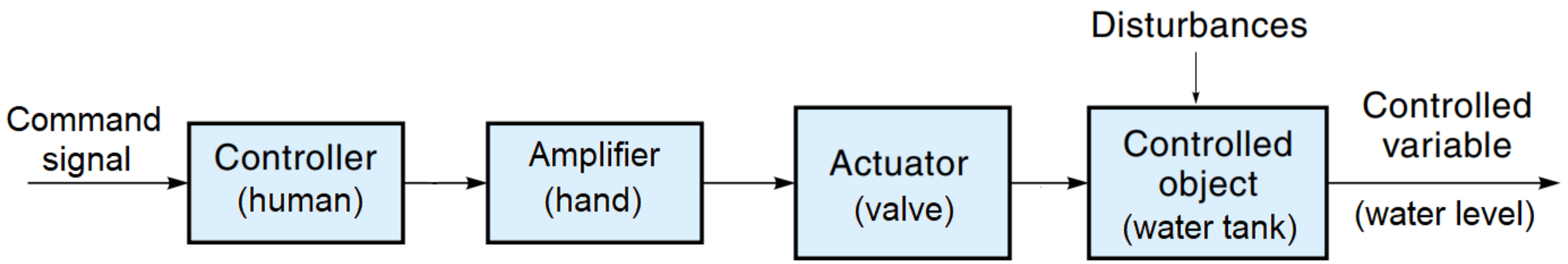


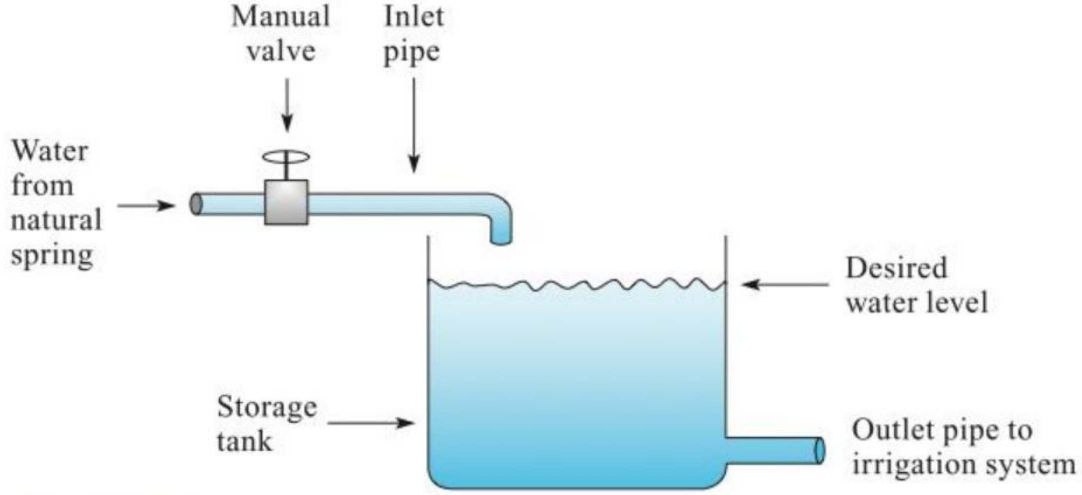
- **Reference Signal / Set Point:** Required set point or command signal to achieve the desired control objective
- **Control Signal / Control Variable:** The signal we use to control the system
- **Manipulated Variable:** The regulated signal by the actuator as the final control element
- **Output Signal / Process Variable / Controlled Variable:** The measured data or signal from the system to check its behavior
- **Disturbance:** Environmental perturbations that are harming the system

Basic Elements of an Open-loop Control System

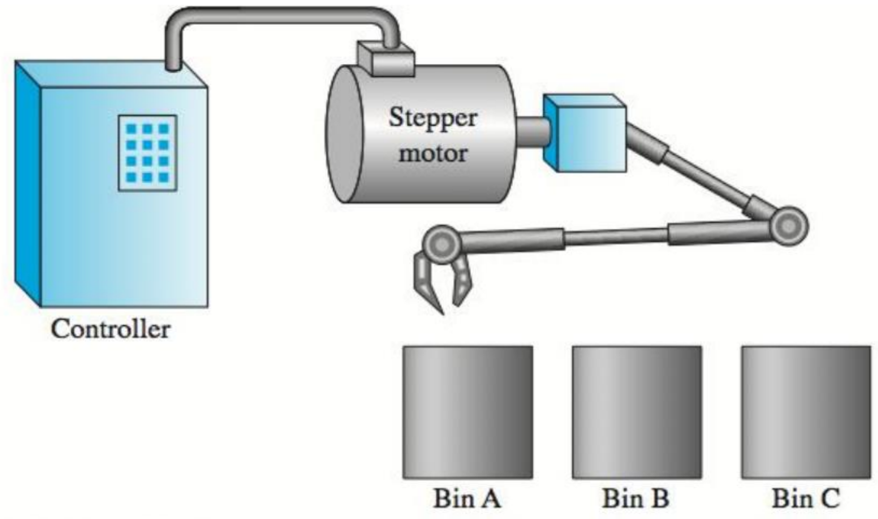
Example

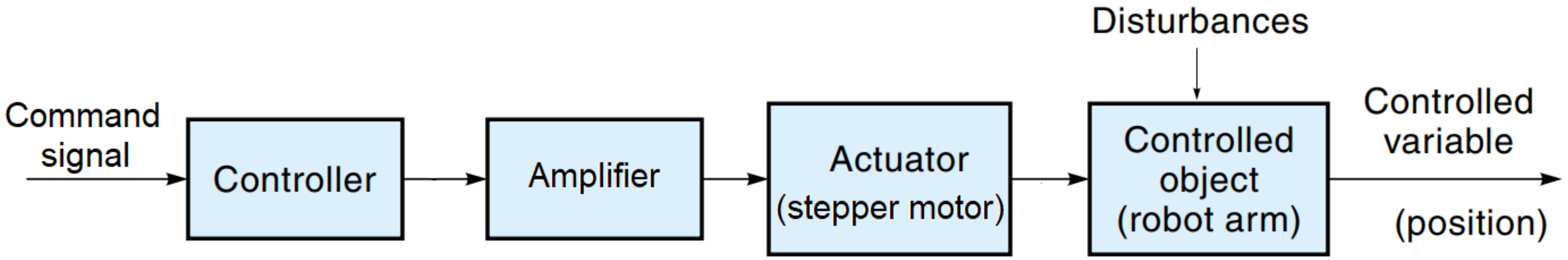
- An Open-loop Reservoir System to Store Water for an Irrigation System





- An Open-loop Pick-and-Place Application

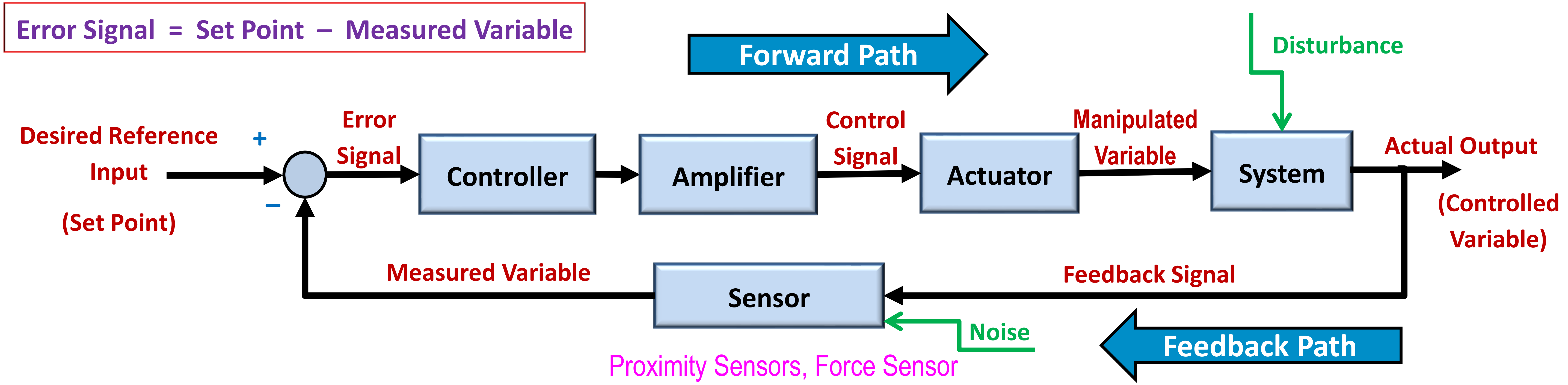




Basic Elements of a Closed-loop Control System

- In addition to the elements of the open-loop control system the following elements are exist in a closed-loop control system:
  - **Sensor / Measurement Device (The eyes):** It provides the controller information about the controlled variable or measured output
  - **Feedback Signal:** The measure value of the actual output
  - **Measured Value:** With an accurate sensor, the measured output is a good approximation of the actual output of the system
  - **Error Detector:** This element compares the required value of the variable being controlled with the measured value and produces an error signal
  - **Error Signal:** Difference between the reference input and the measured output

Error Signal = Set Point – Measured Variable



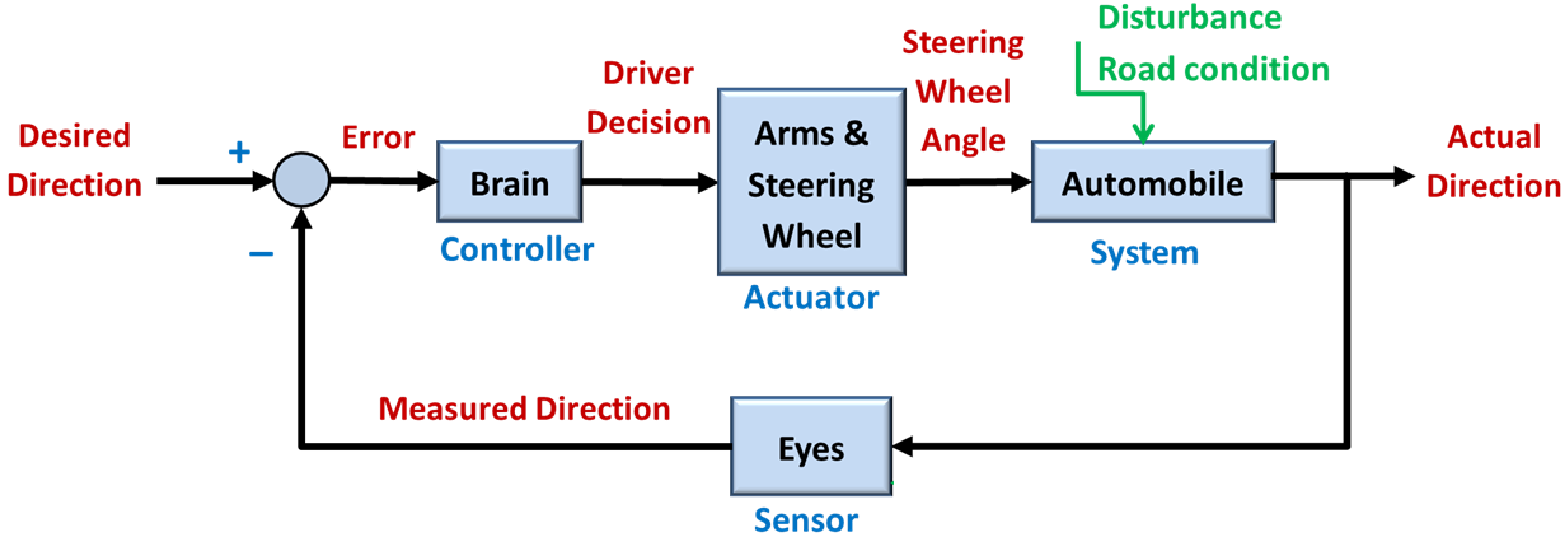
Proximity Sensors, Force Sensor
Thermocouple, Pressure Sensor
Tachometer, Potentiometer, Encoder

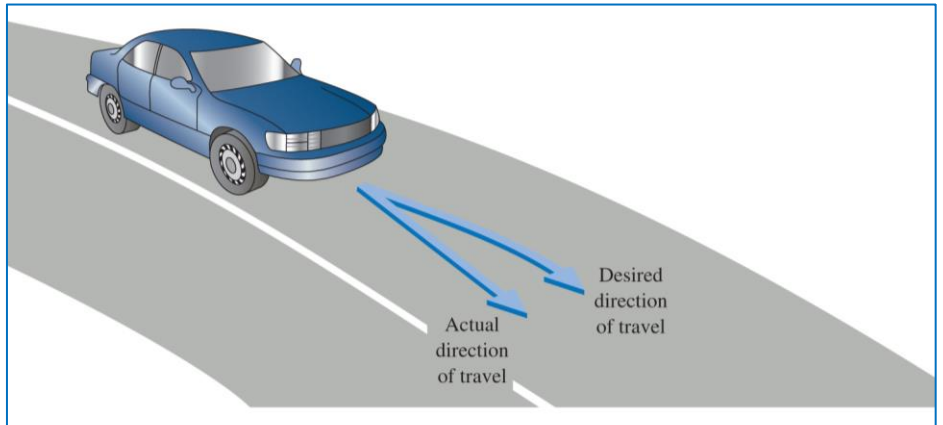
Basic Elements of a Closed-loop Control System

Example

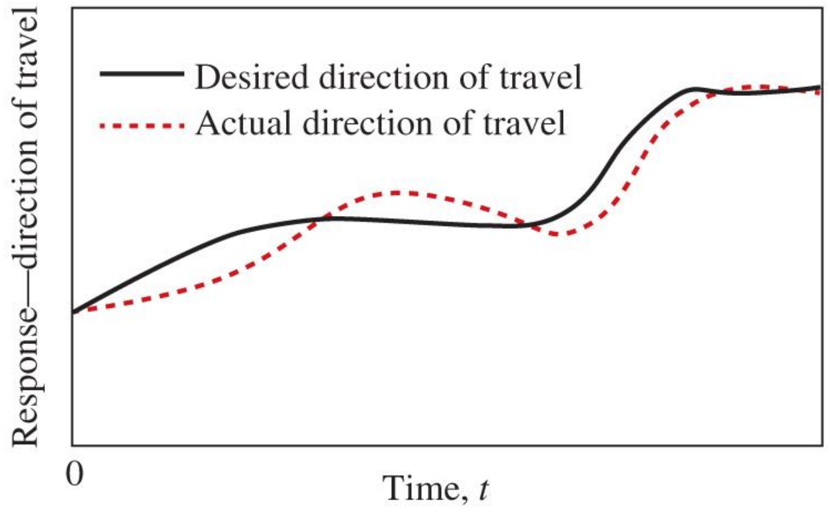
❑ Automobile Navigation Control

- An operator monitors and adjusts the system
- This is a human-in-the-loop control





(b)



(c)

Error Signal = Desired Direction – Measured Direction

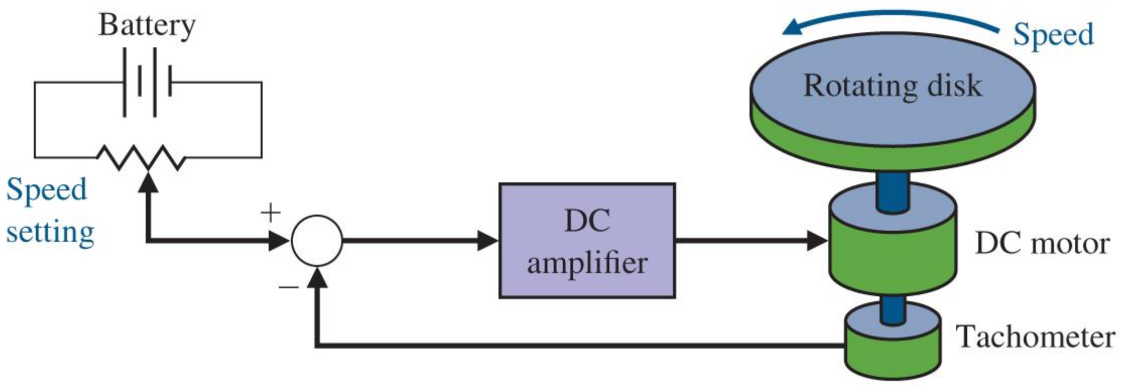
Basic Elements of a Closed-loop Control System

Example

❑ Rotating Disk Speed Control

- This is an automated closed-loop control system

- The goal is to design a system for rotating disk speed control that will ensure that the actual speed of rotation is within a specified percentage of the desired speed.



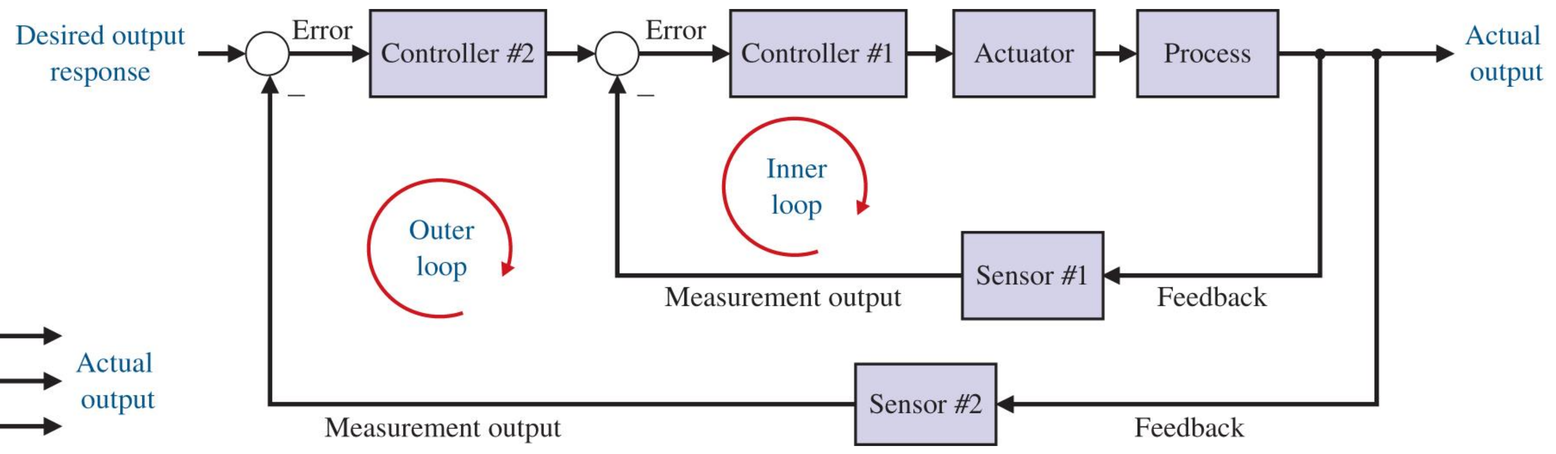
- The battery source provides a voltage that is proportional to the desired speed.
- This voltage is amplified and applied to the motor.
- A DC motor is selected as the actuator because it provides a speed proportional to the applied motor voltage.

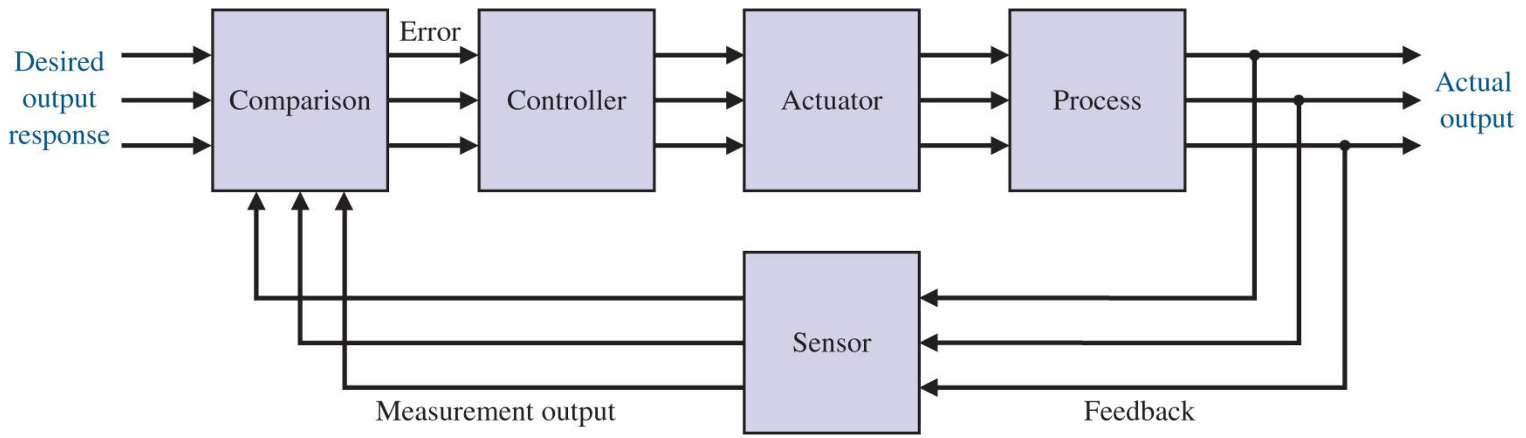
- To obtain a feedback system, we need to select a sensor.
- A tachometer can provide an output voltage proportional to the speed of fix shaft.

Error Signal = Desired Speed − Tachometer Speed

Multi-loop & Multivariable Feedback Control Systems

- In addition to the basic single-loop, single-input and single-output feedback control systems, there are several more complex configurations.
- Many feedback control systems contain more than one feedback loop.
- A common **multi-loop feedback control system** is a one with an **inner loop** and an **outer loop**.
- In this scenario, the inner loop has a controller and a sensor, and the outer loop has a controller and sensor





- In some cases, due to the increasing complexity of the system under control and the interest in achieving optimum performance, the interrelationship of many controlled variables must be considered in the control scheme by configuring a **multivariable control system.**

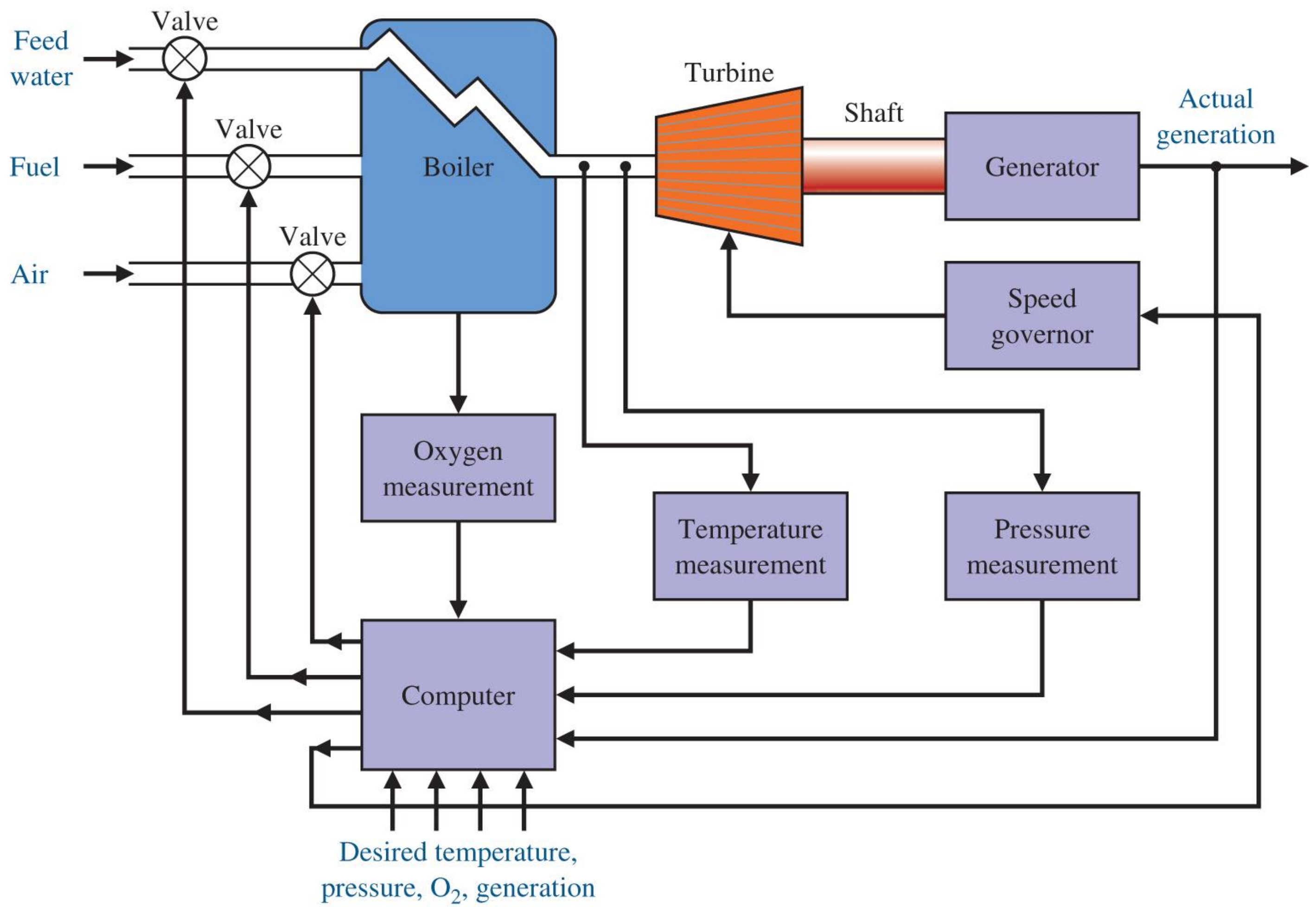
Multi-loop & Multivariable Feedback Control Systems

Example

❑ Electric Power Industry

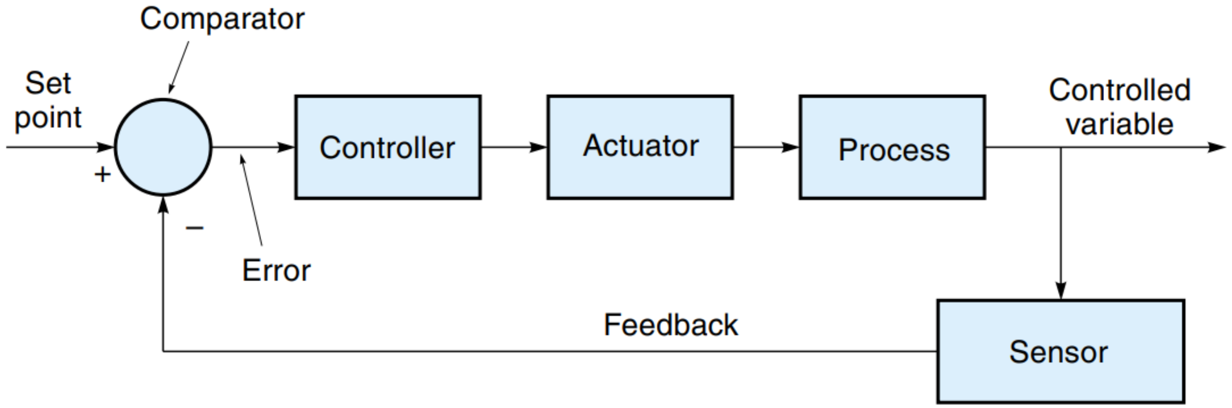
- This is a coordinated control system for a boiler–generator

- The electric power industry is primarily interested in energy conversion, control, and distribution.
- It is critical that computer control be increasingly applied to the power industry in order to improve the efficient use of energy resources.
- Also, the control of power plants for minimum waste emission has become increasingly important.
- A simplified model showing several of the important control variables of a large boiler–generator system.
- This is an example of the importance of measuring many variables, such as pressure and oxygen, to provide information to the computer for control calculation.

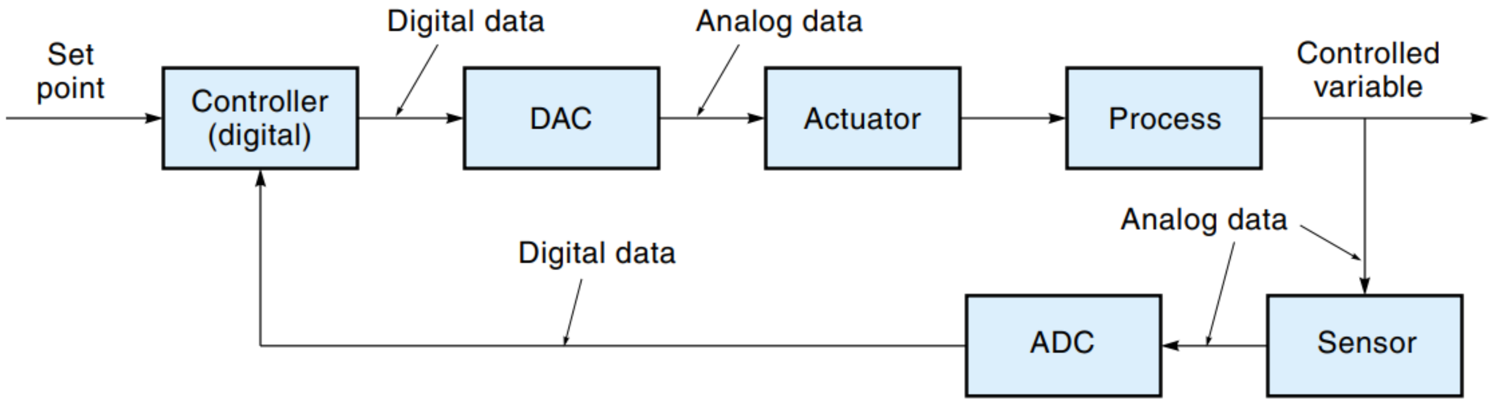


Analog & Digital Control Systems

- In an **analog control system**, the controller consists of traditional analog devices and circuits, that is, **linear amplifiers**.
- The first control systems were analog because it was the only available technology.
- In the analog control system, any change in either set point or feedback is sensed immediately, and the amplifiers adjust their output (to the actuator) accordingly.



- A **digital control system** uses digital signals and a digital computer to control a process.
- The measurement data are converted from analog form to digital form by means of the analog-to-digital converter (ADC)
- After processing the inputs, the digital computer provides an output in digital form.
- This output is then converted to analog form by the digital-to-analog converter (DAC).



Control System Design Procedure

1. Establishment of goals, variables to be controlled, and specifications

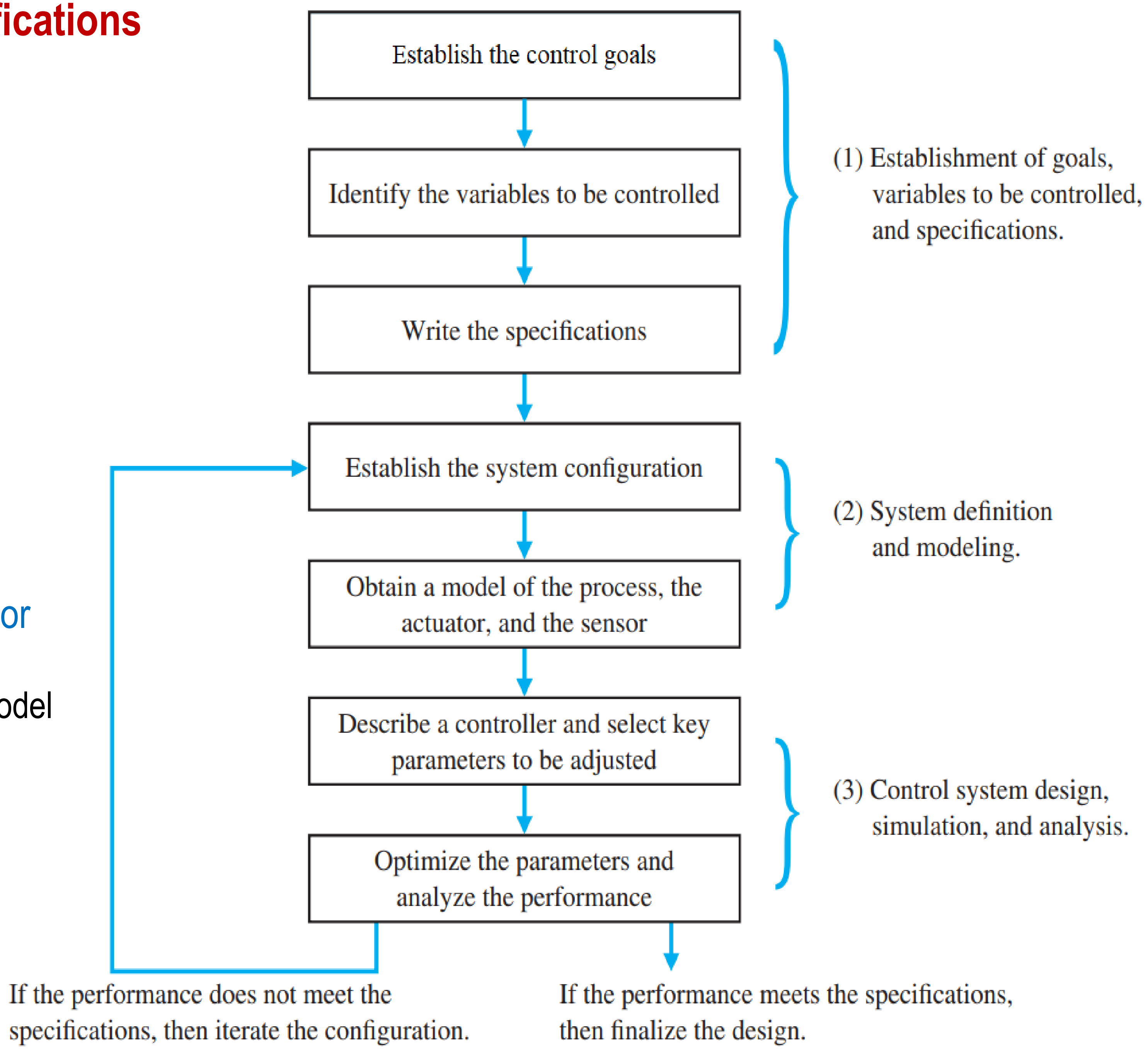
- Establish the control goals and objectives
  - Stability, Regulation, Tracking, Robustness, Cost & Efficiency, …
- Identify the variables to be controlled
  - Input Signal, Output Signal, …
- Write the desired performance specifications
  - Response time, Accuracy, …

2. System definition and modeling

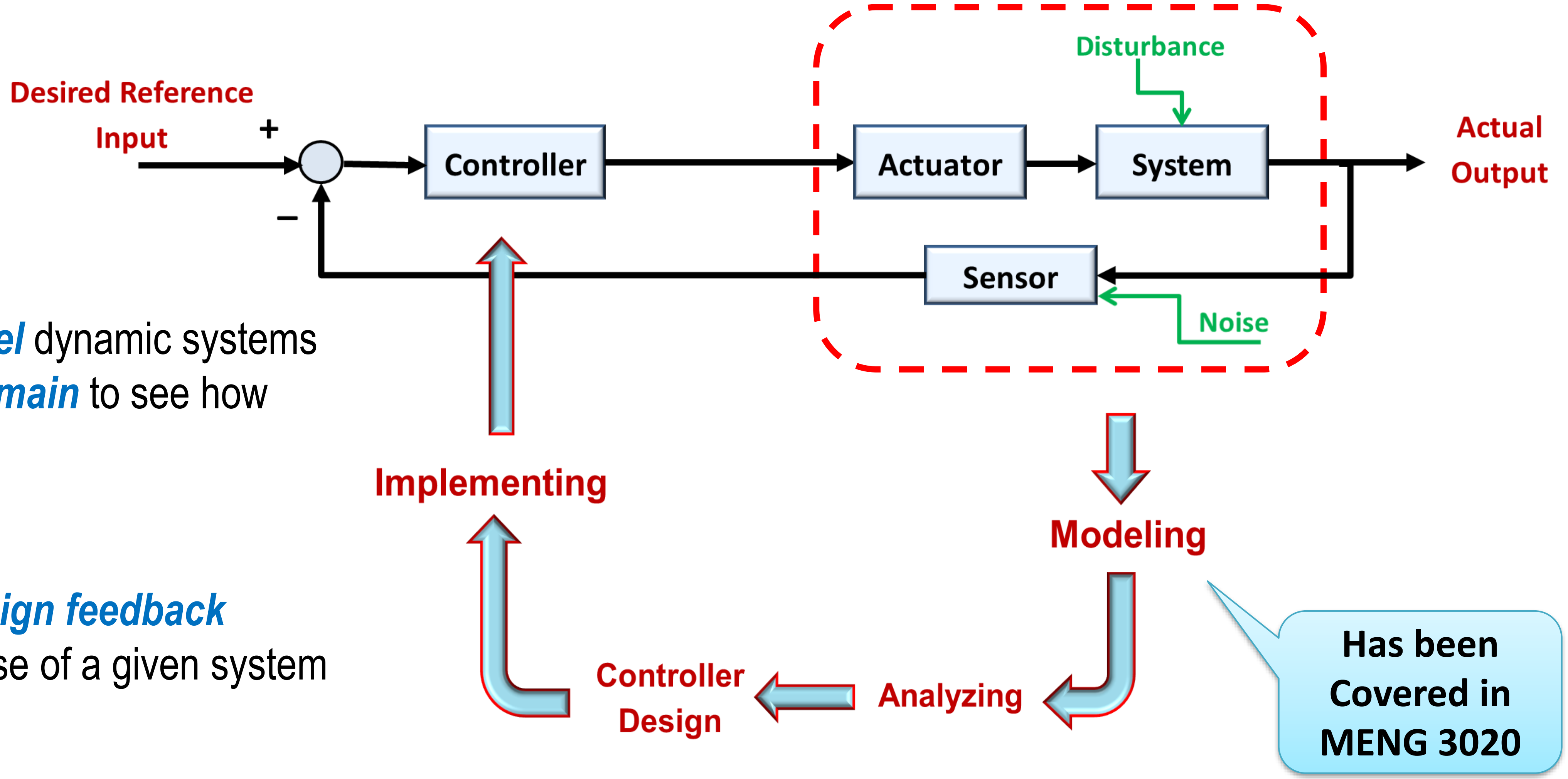
- Establish the system configuration
  - Open-loop, Closed-loop, Components, …
- Obtain a model of the process/system, amplifier, actuator, and sensor
  - Mathematical techniques that involves differential equation solution, Empirical methods, Block diagram, Transfer function, State-space Model

3. Control system design, simulation, and analysis

- Analyze the system to check the characteristics
- Describe a controller and select key parameters to be adjusted
- Optimize the parameters and analyze the performance
- Compare the performance with the desired specifications including stability, transient response, steady-state response, …



Control System Design Procedure



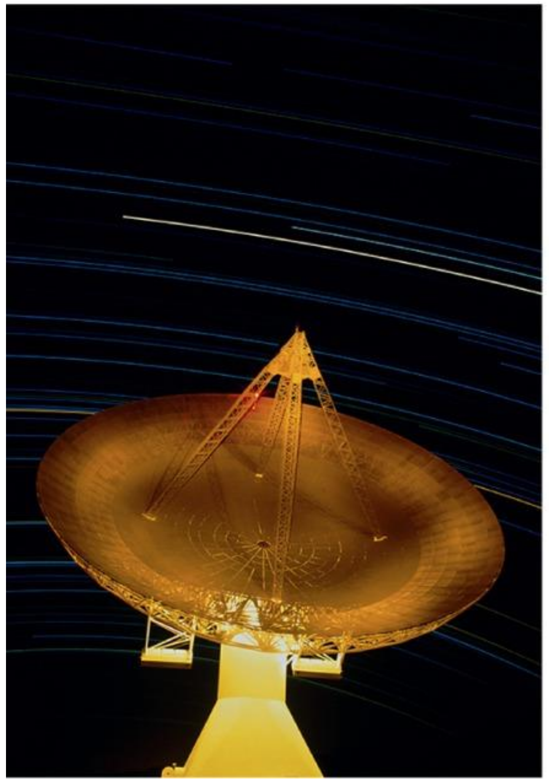
- In **MENG 3020**, you learned how to ***model*** dynamic systems and ***simulate*** their responses in ***time domain*** to see how does a given system respond.

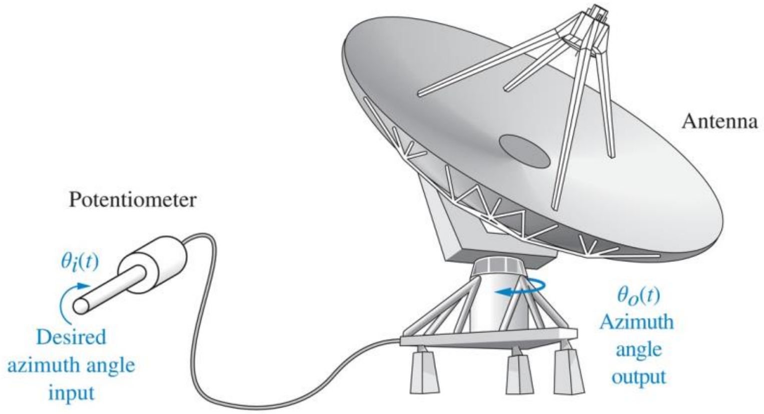
- In **MENG 3510**, you will learn how to ***design feedback control systems*** to ***improve*** the response of a given system in three primary areas:
  - ***Dynamic response***
  - ***Steady-state error***
  - ***Stability***

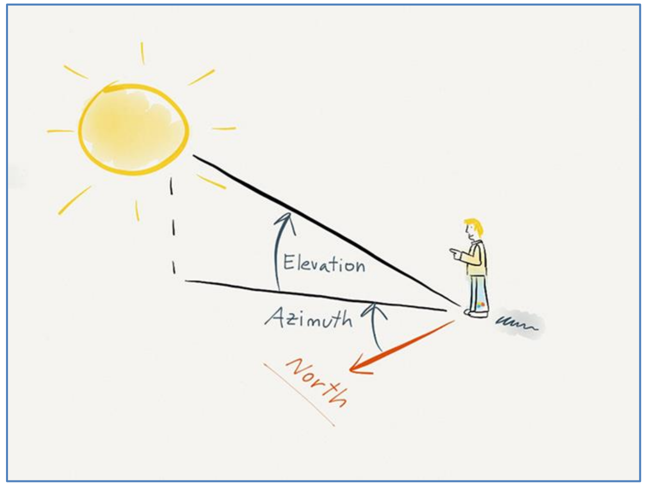
Review of
Dynamic System Modeling

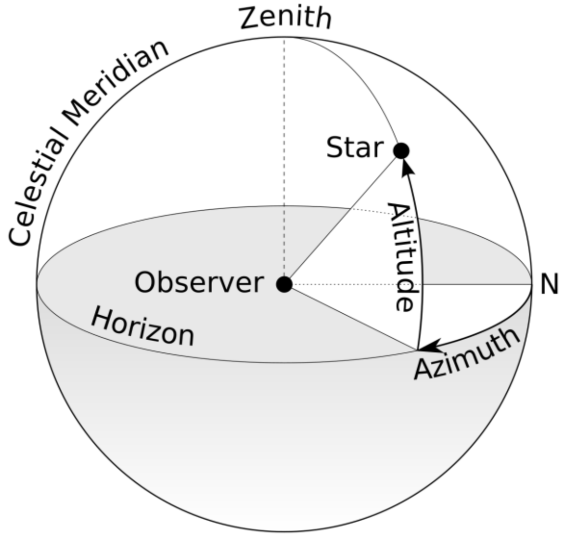
Review of Dynamic System Modeling

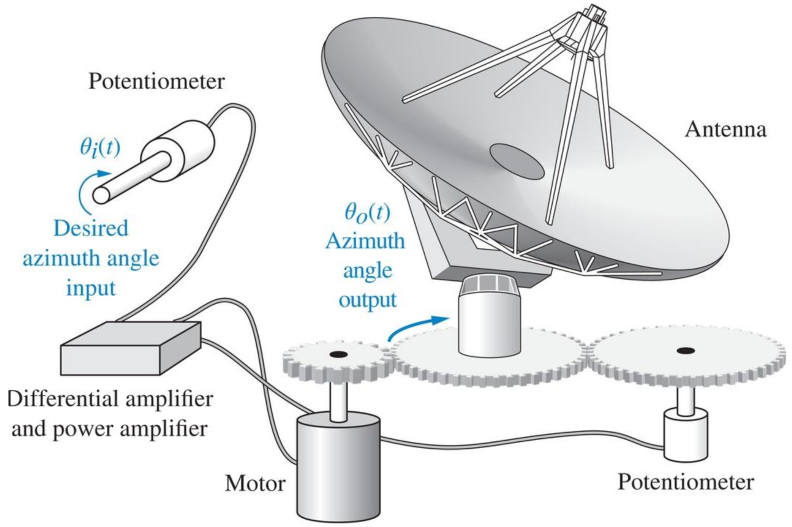
- The design of a feedback control system requires first having a model of the system to be controlled.
- This sub-section provides a review of dynamic system modeling and analysis fundamentals.
- In this section, we will take a look at a simple ***motor-driven antenna azimuth position control system*** example to review dynamic system modeling fundamentals.
  - Create Schematic & Block diagram
  - Differential equation models
  - Transfer function models
  - State-variale models
  - System poles & Transient response





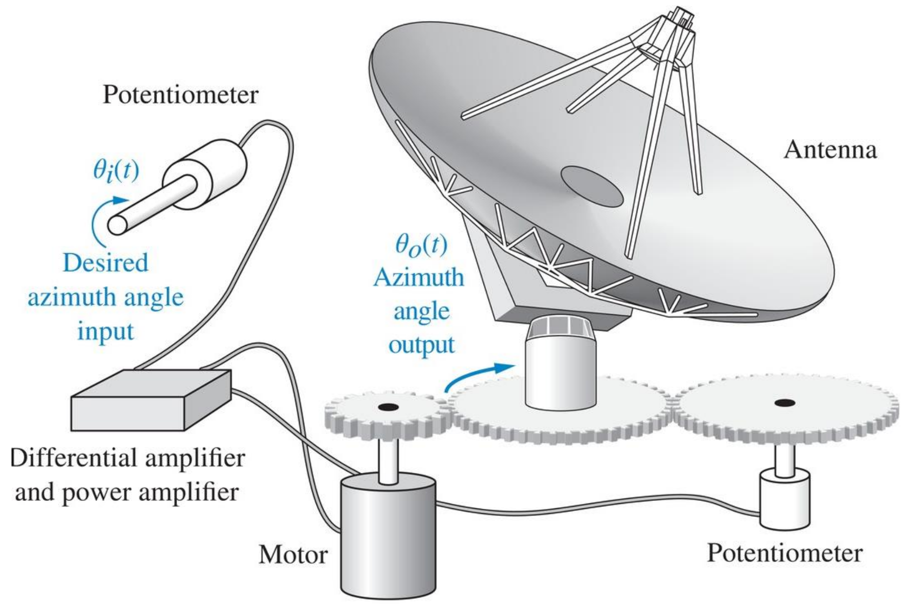




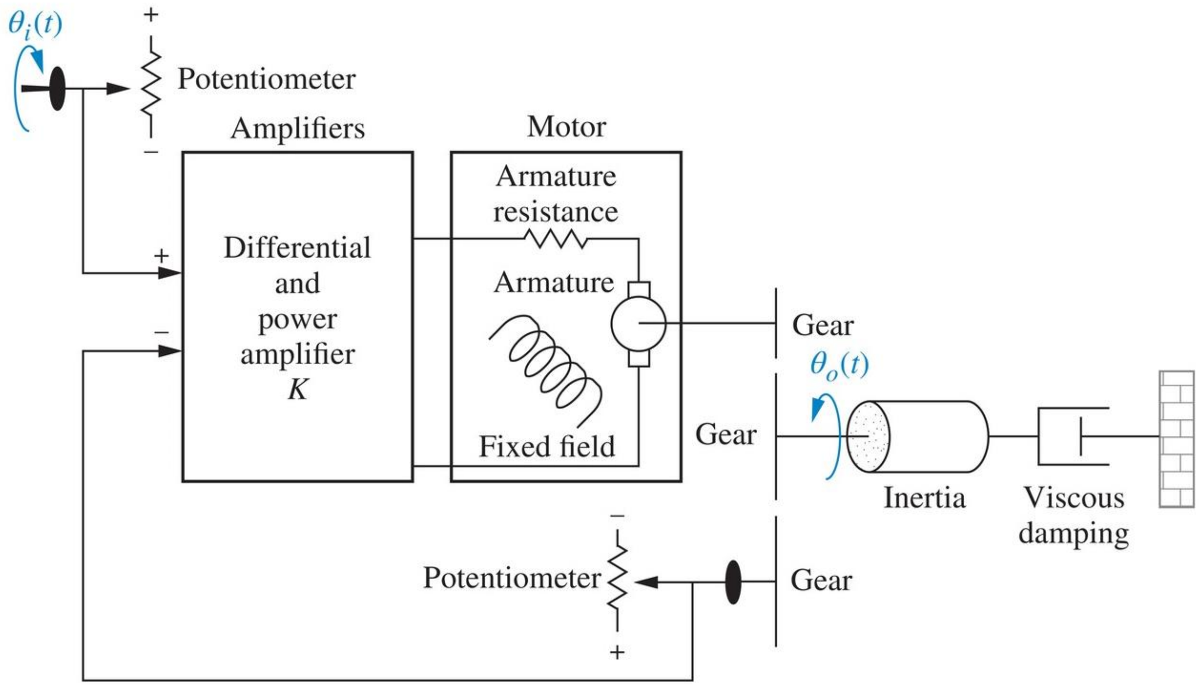


Review of Dynamic System Modeling

❑ Create Schematic & Block Diagram



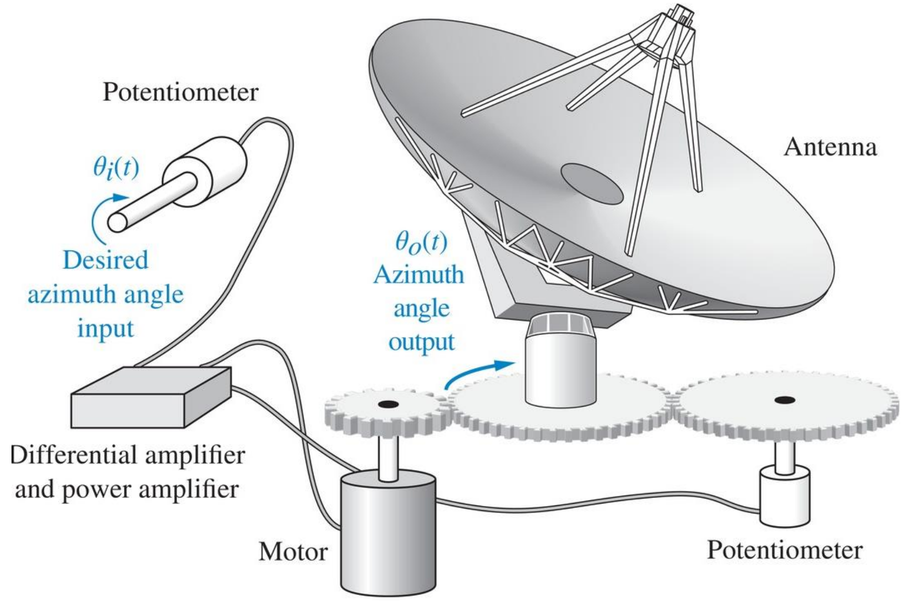
- Transform the physical system into a schematic diagram by making some simplifying assumptions.
- We must make approximations about the system and neglect certain phenomena, or else the schematic will be unwieldy, making it difficult to extract a useful mathematical model during the next phase of the analysis and design sequence.
- **Potentiometers**: Assume that the mechanical effects, friction and inertia, are negligible and that the voltage across a potentiometer changes instantaneously as the potentiometer shaft turns.
- **Amplifiers**: Assume that the dynamics of the differential amplifier is rapid compared to the response time of the power amplifier and the motor. Thus, we model it as a pure gain.
- **DC Motor**: Assume that the effect of armature inductance is negligible for DC motor.
- **Load**: The load consists of a rotating mass and bearing friction. Thus, the model consists of inertia and viscous damping.

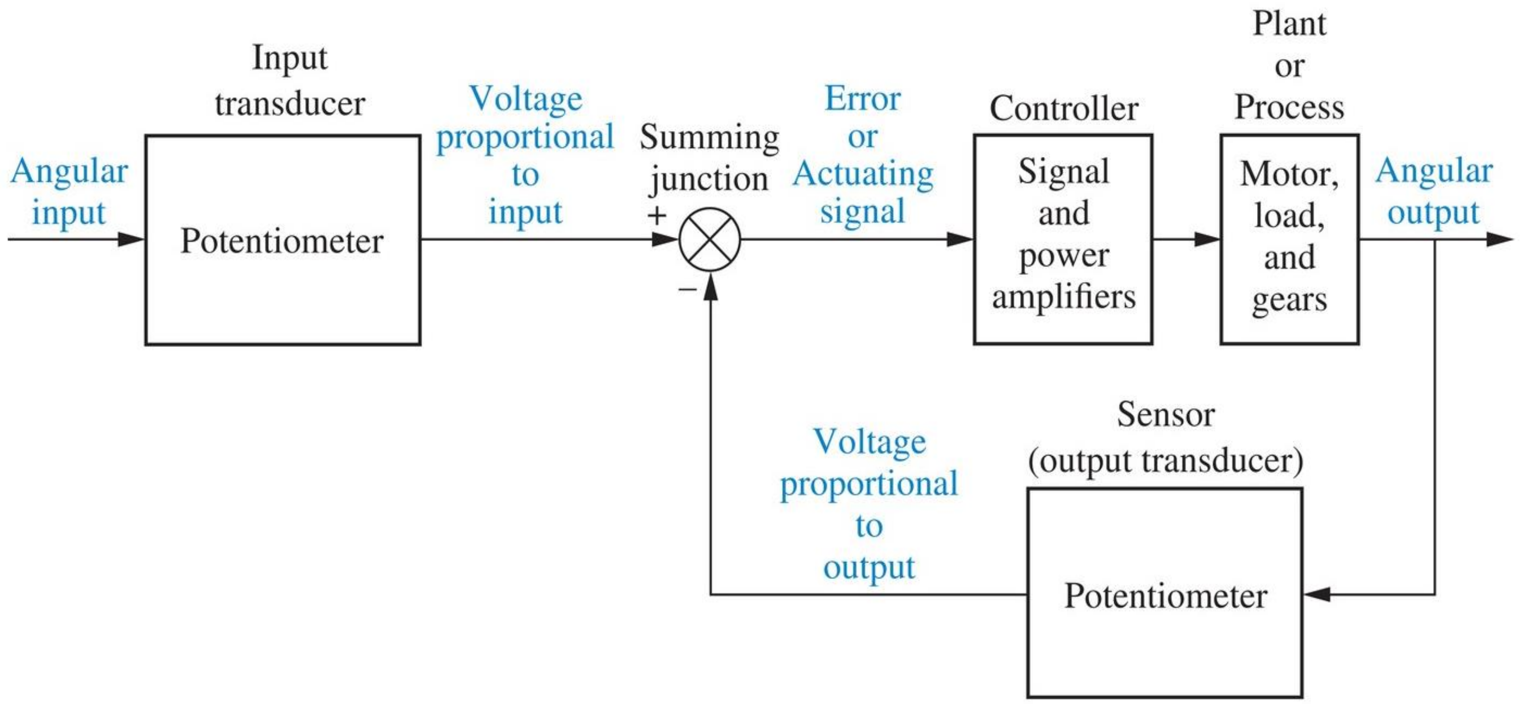


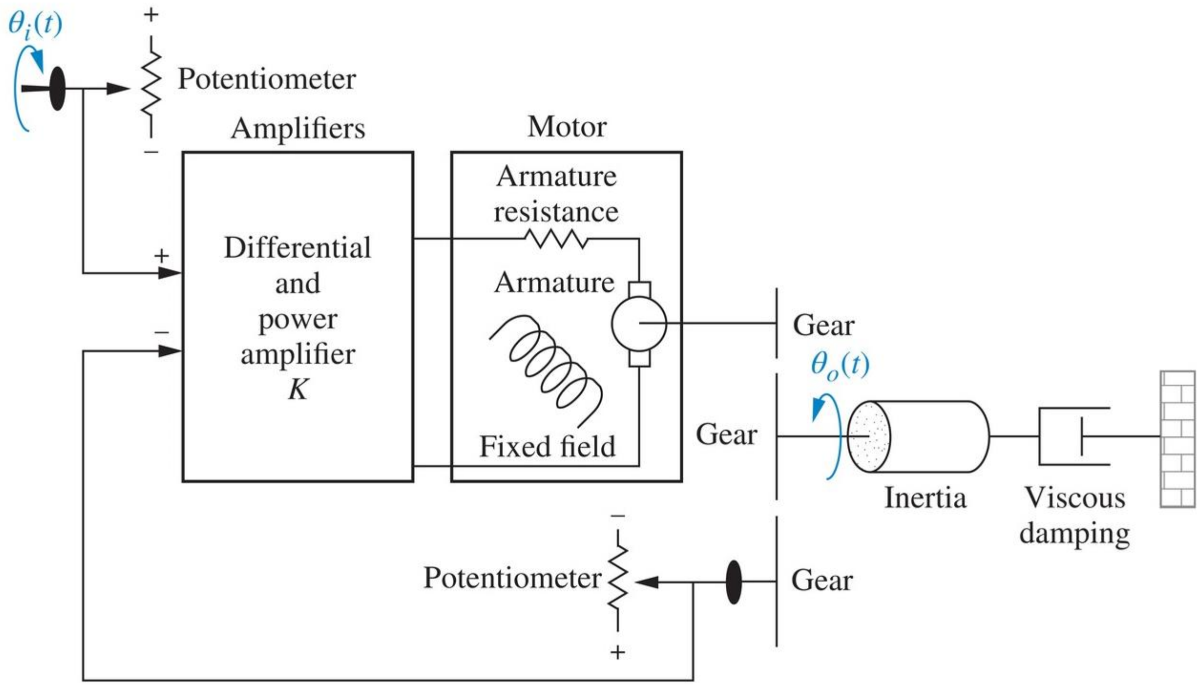
Review of Dynamic System Modeling

❑ Create Schematic & Block Diagram

- We can translate a qualitative description of the system into a functional block diagram that describes the component parts or subsystems of the system and shows their interconnection and input-output.



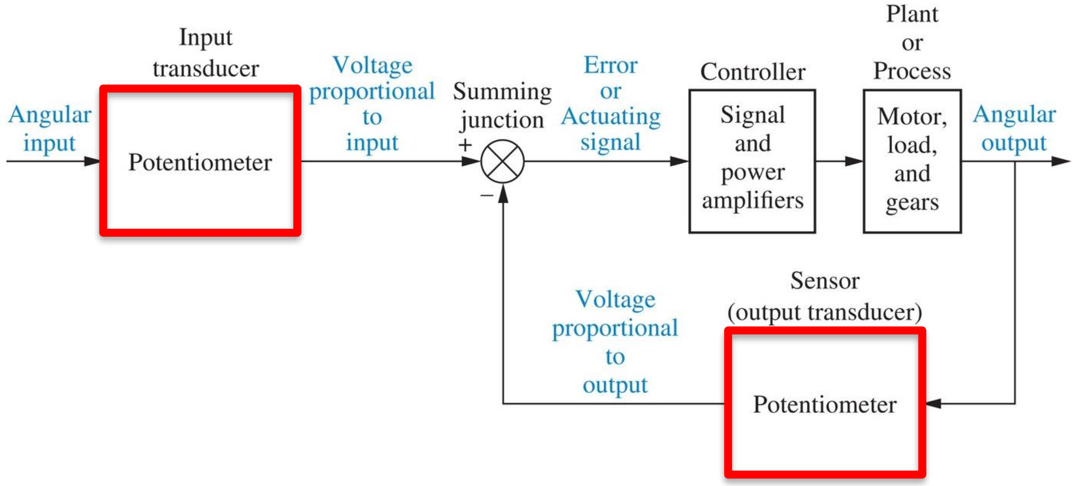


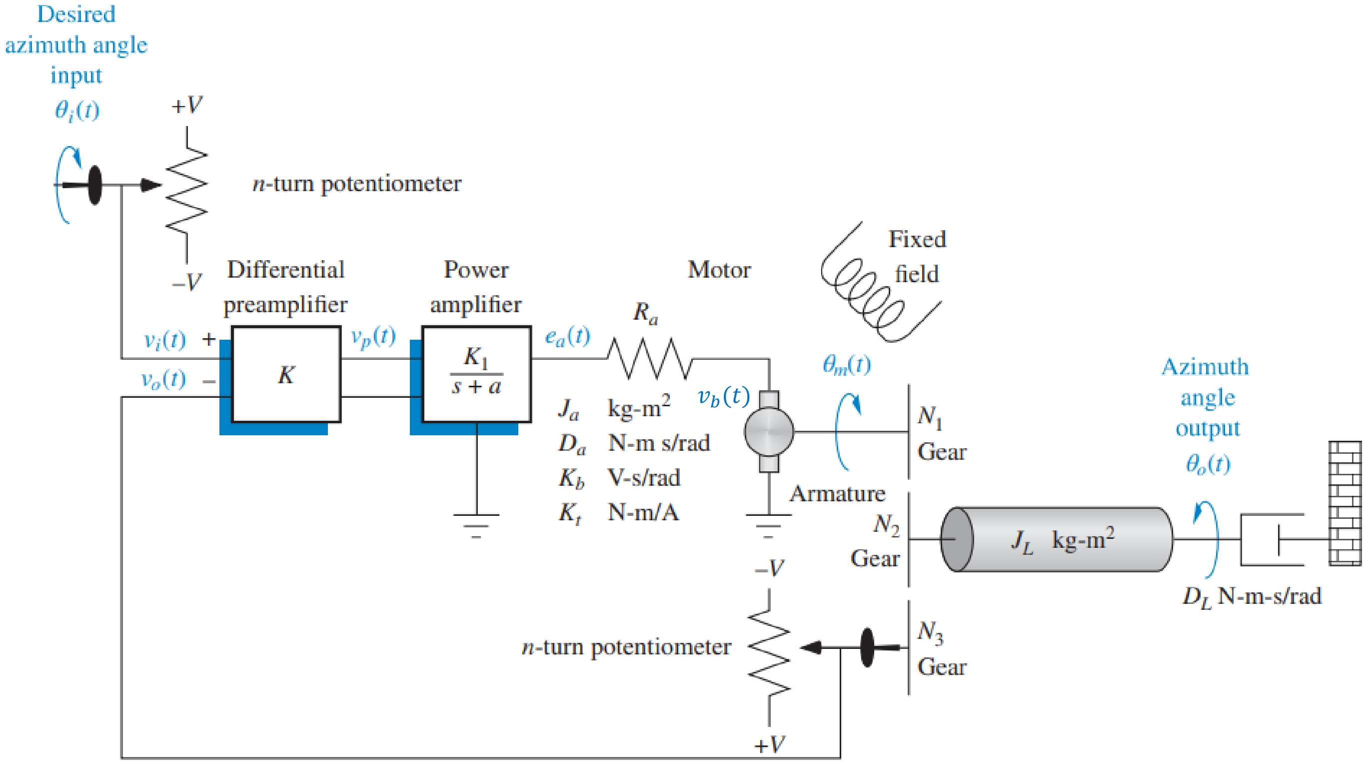


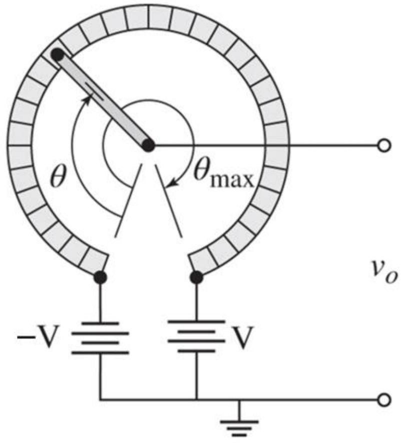
Review of Dynamic System Modeling

❑ Develop a Mathematical Model

- Define the input-output and find a transfer function model for each subsystem.
- **Input Potentiometer & Output Potentiometer**:
  - Since the input and output potentiometers are configured in the same way, their transfer functions will be the same.
  - We neglect the mechanical dynamics for the potentiometers and simply find the relationship between the output voltage and the input angular displacement.







$$\frac{v_o(t)}{\theta(t)} = \frac{2V}{\theta_{max}} = \frac{2V}{2\pi} = \frac{V}{\pi} = K_{pot}$$

$$\boxed{\frac{V_o(s)}{\theta(s)} = K_{pot}}$$

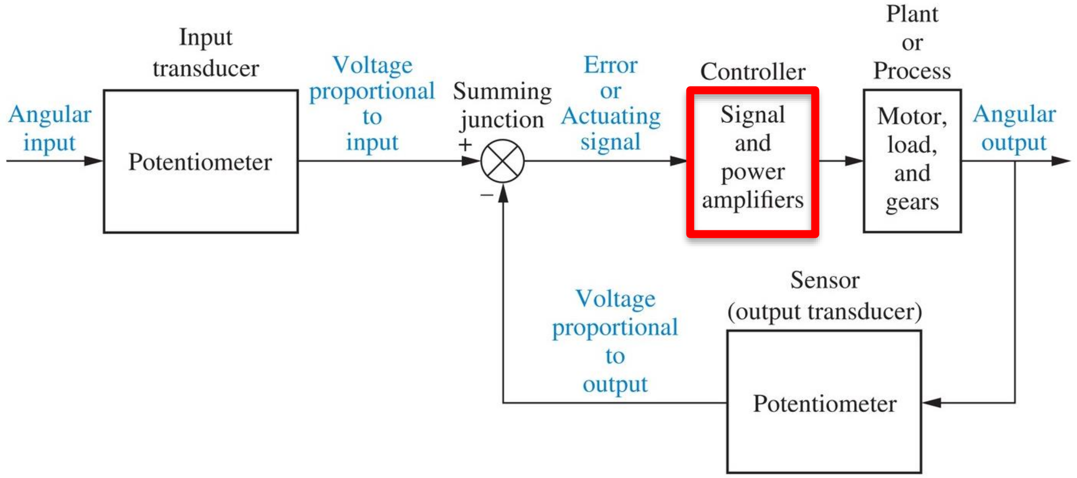
- Assume $V = 10V$:

$$\frac{V_o(s)}{\theta(s)} = \frac{10}{\pi} = 0.318$$

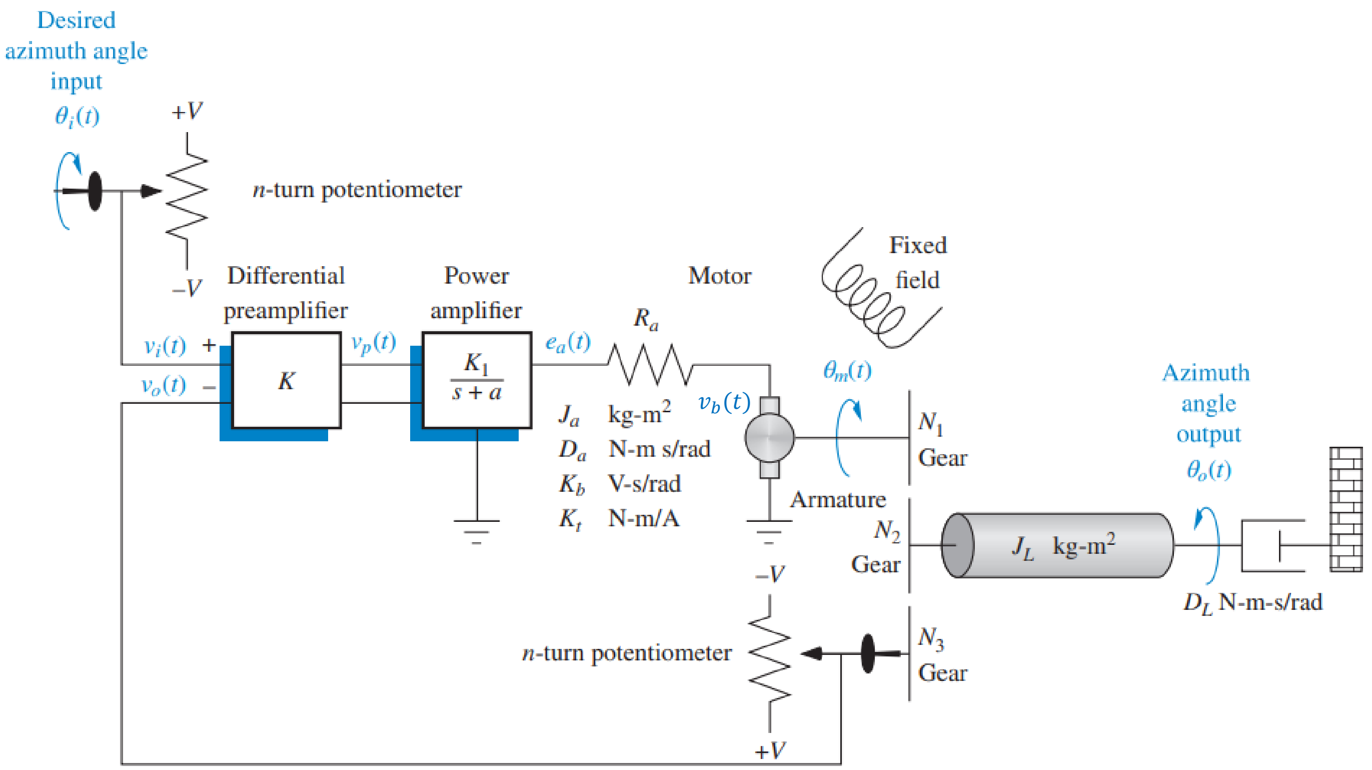
Review of Dynamic System Modeling

❑ Develop a Mathematical Model

- Define the input-output and find a transfer function model for each subsystem.



- **Signal & Power Amplifiers**:
  - First, we assume that saturation is never reached.
  - Second, the dynamics of the differential preamplifier are neglected, since its speed of response is typically much greater than that of the power amplifier.



- **Signal Amplifier**:

$$\boxed{\frac{V_p(s)}{V_e(s)} = K}$$

- **Power Amplifier**:

$$\boxed{\frac{E_a(s)}{V_p(s)} = \frac{K_1}{s+a}}$$

- Assume $K_1 = 100, \quad a = 100$:

$$\frac{E_a(s)}{V_p(s)} = \frac{100}{s+100}$$

Review of Dynamic System Modeling

❑ Develop a Mathematical Model

- Define the input-output and find a transfer function model for each subsystem.
- **DC Motor & Load**:
  - Differential equation of electrical and mechanical subsystems:

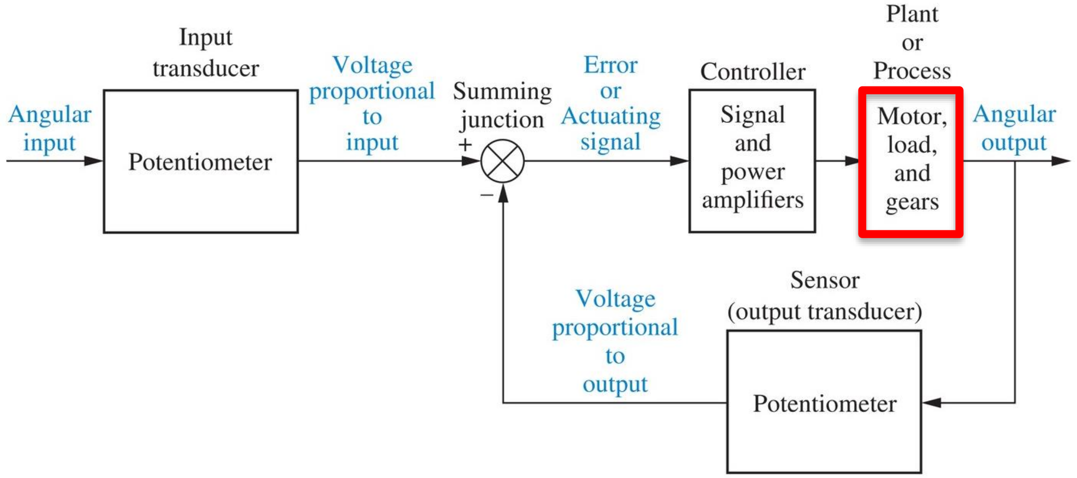
$$\begin{cases} R_a i_a(t) + v_b(t) = e_a(t) \\ v_b(t) = k_b \dot{\theta}_m(t) \end{cases}$$

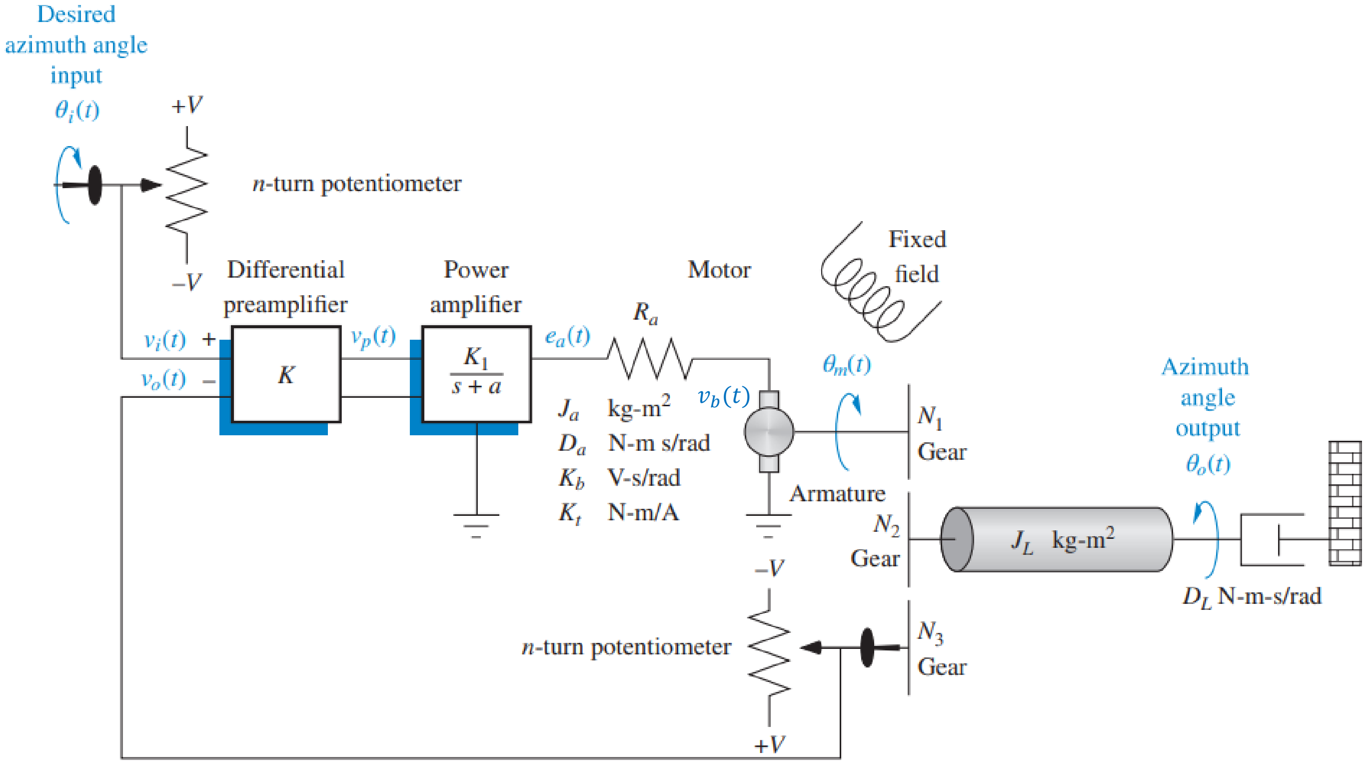
$$\begin{cases} \tau_m(t) = J_m \ddot{\theta}_m(t) + D_m \dot{\theta}_m(t) \\ \tau_m(t) = k_t i_a(t) \end{cases}$$

  - The equivalent inertia and the equivalent viscous damping in the motor-side are obtained by applying the gear ratio,

$$J_m = J_a + J_L \left(\frac{1}{N}\right)^2$$

$$D_m = D_a + D_L \left(\frac{1}{N}\right)^2$$





Review of Dynamic System Modeling

❑ Develop a Mathematical Model

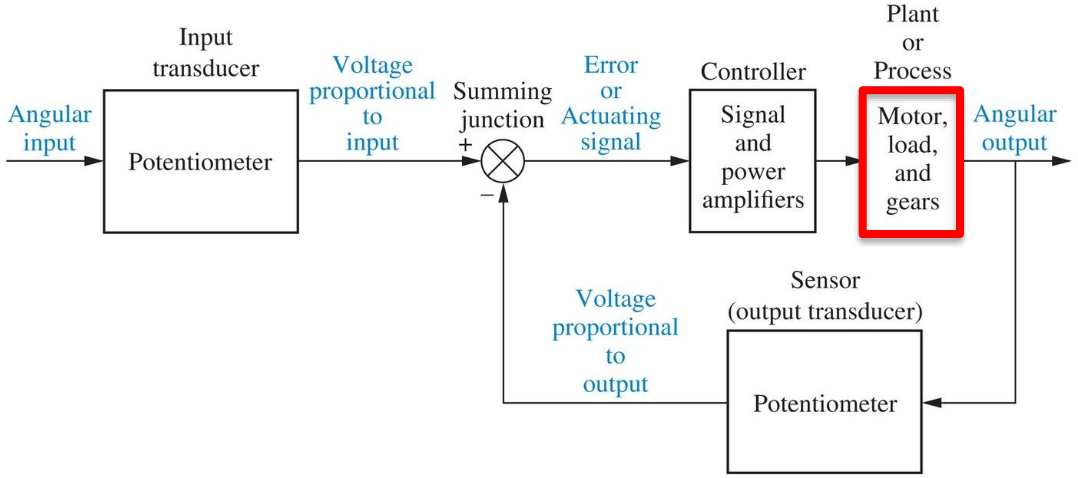
- Define the input-output and find a transfer function model for each subsystem.
- **DC Motor & Load**:
  - Taking Laplace transform and combing the equations, we can find the transfer function model of the motor-load subsystem:

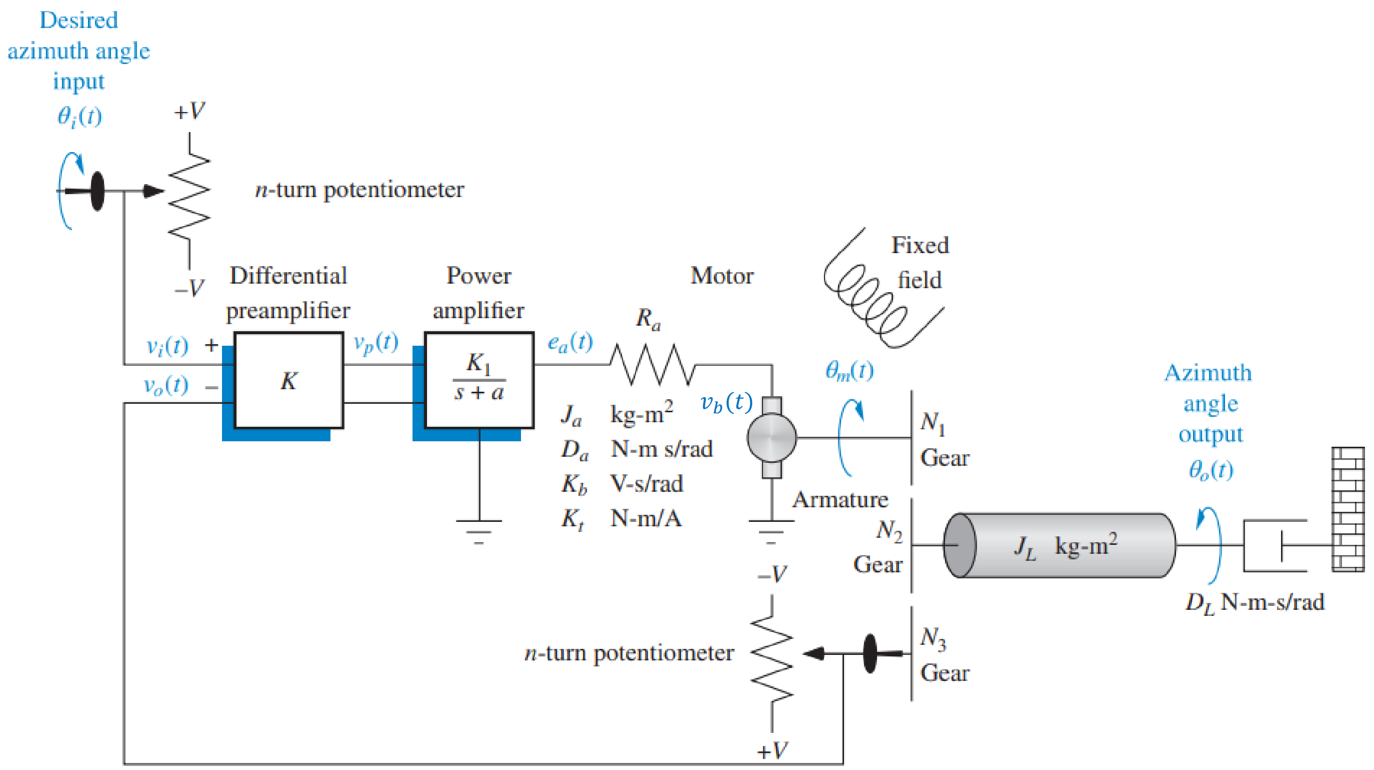
$$\begin{cases} R_a I_a(s) + V_b(s) = E_a(s) \\ V_b(s) = k_b s\theta_m(s) \end{cases}$$

$$\begin{cases} T_m(s) = J_m s^2\theta_m(s) + D_m s\theta_m(s) \\ T_m(s) = k_t I_a(s) \end{cases}$$

  - The transfer function model is:

$$\boxed{\frac{\theta_m(s)}{E_a(s)} = \frac{\frac{k_t}{R_a J_m}}{s\left(s + \frac{1}{J_m}\left(D_m + \frac{k_t k_b}{R_a}\right)\right)} = \frac{K_m}{s(s+a_m)}}$$

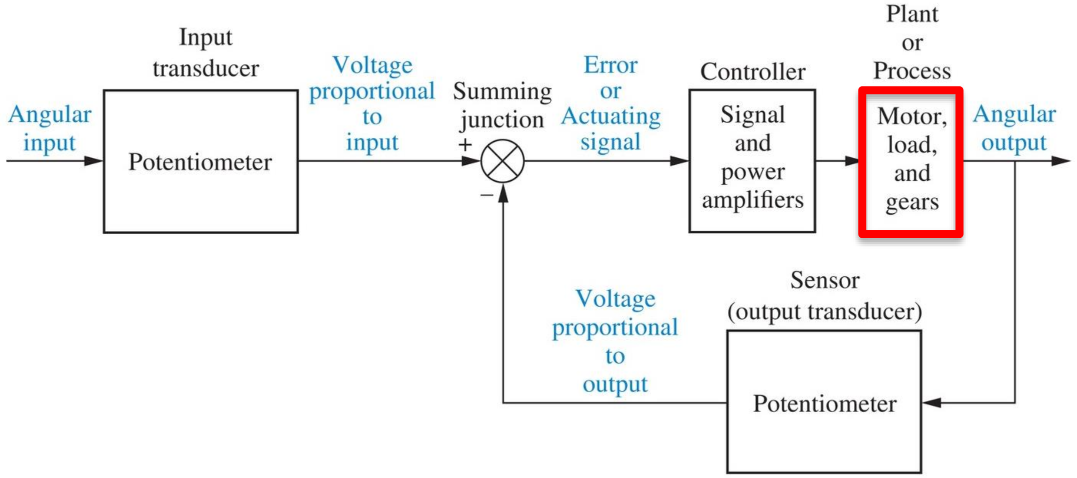




Review of Dynamic System Modeling

❑ Develop a Mathematical Model

- Define the input-output and find a transfer function model for each subsystem.

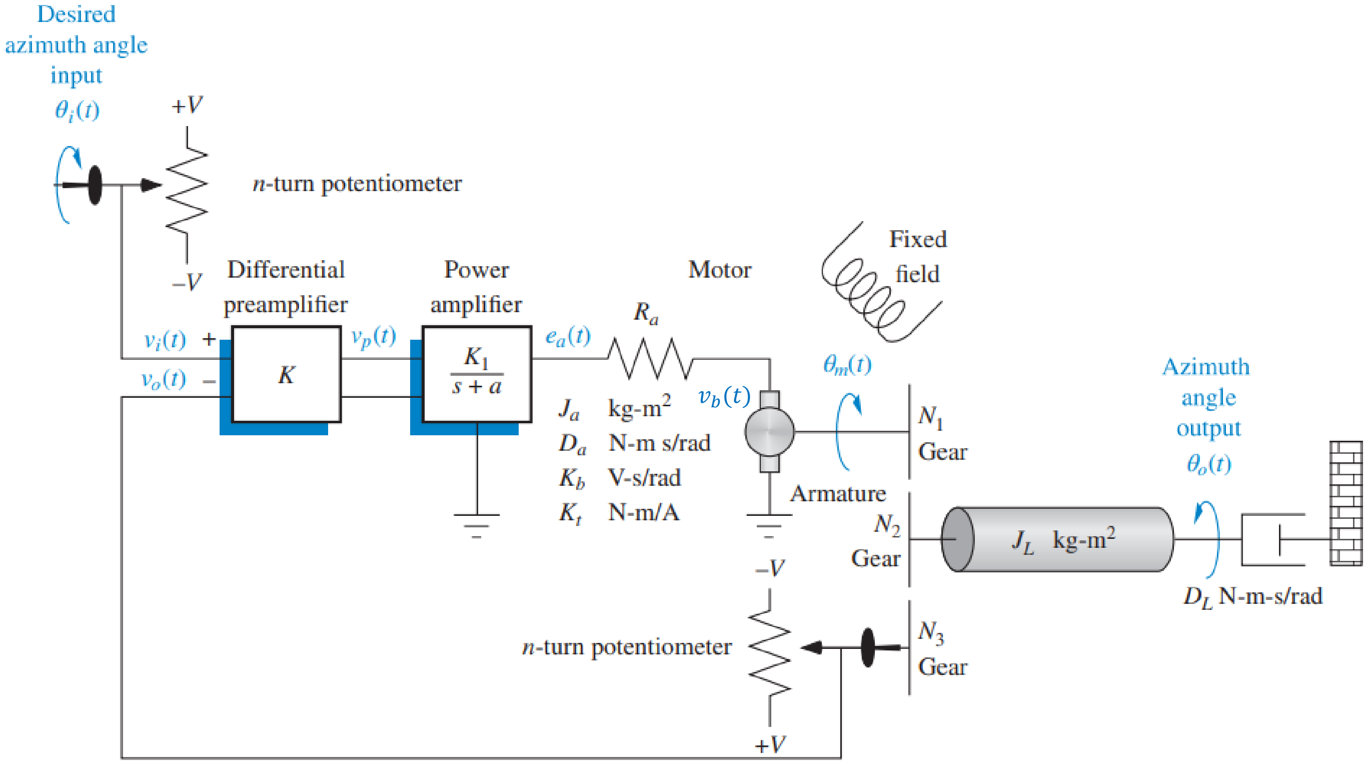


- **DC Motor & Load**:
  - Assume the following values for the system parameters:

$$R_a = 8 \qquad k_b = 0.5 \qquad N = 10$$
$$J_a = 0.02 \qquad k_t = 0.5 \qquad J_L = 1$$
$$D_a = 0.01 \qquad D_L = 1$$

$$J_m = J_a + J_L\left(\frac{1}{N}\right)^2 = 0.02 + 0.01 = 0.03$$

$$D_m = D_a + D_L\left(\frac{1}{N}\right)^2 = 0.01 + 0.01 = 0.02$$



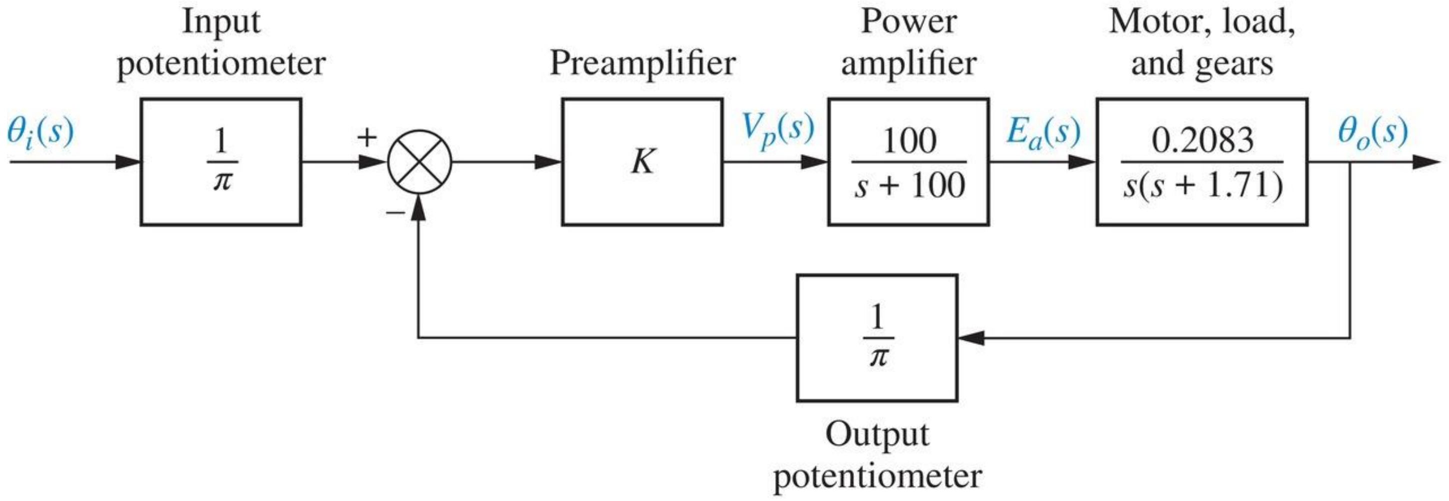
- The transfer function model of DC motor & load is:

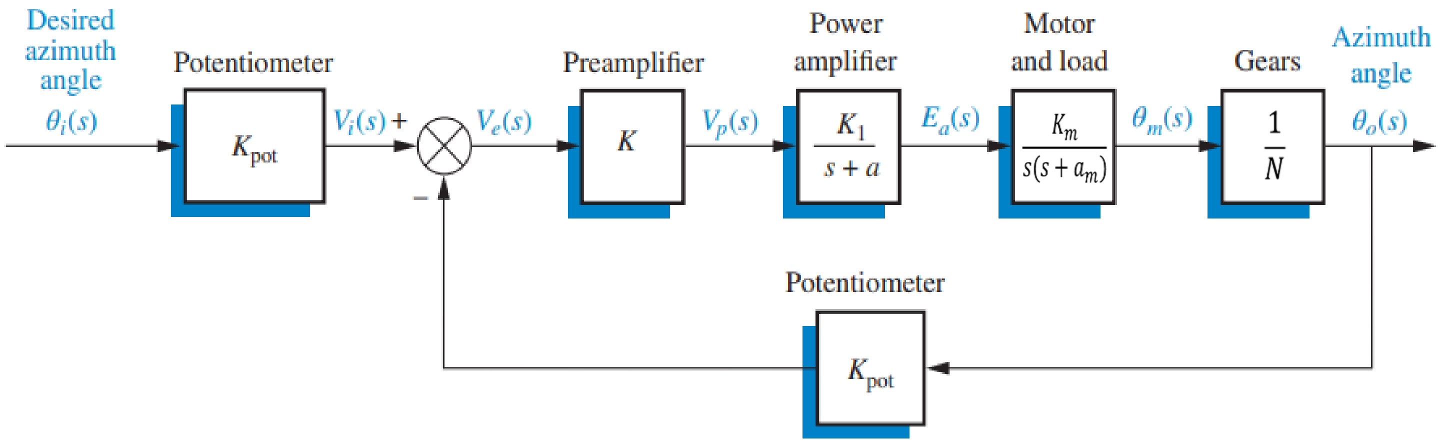
$$\frac{\theta_m(s)}{E_a(s)} = \frac{\frac{k_t}{R_a J_m}}{s\left(s + \frac{1}{J_m}\left(D_m + \frac{k_t k_b}{R_a}\right)\right)} = \frac{2.083}{s(s+1.71)}$$

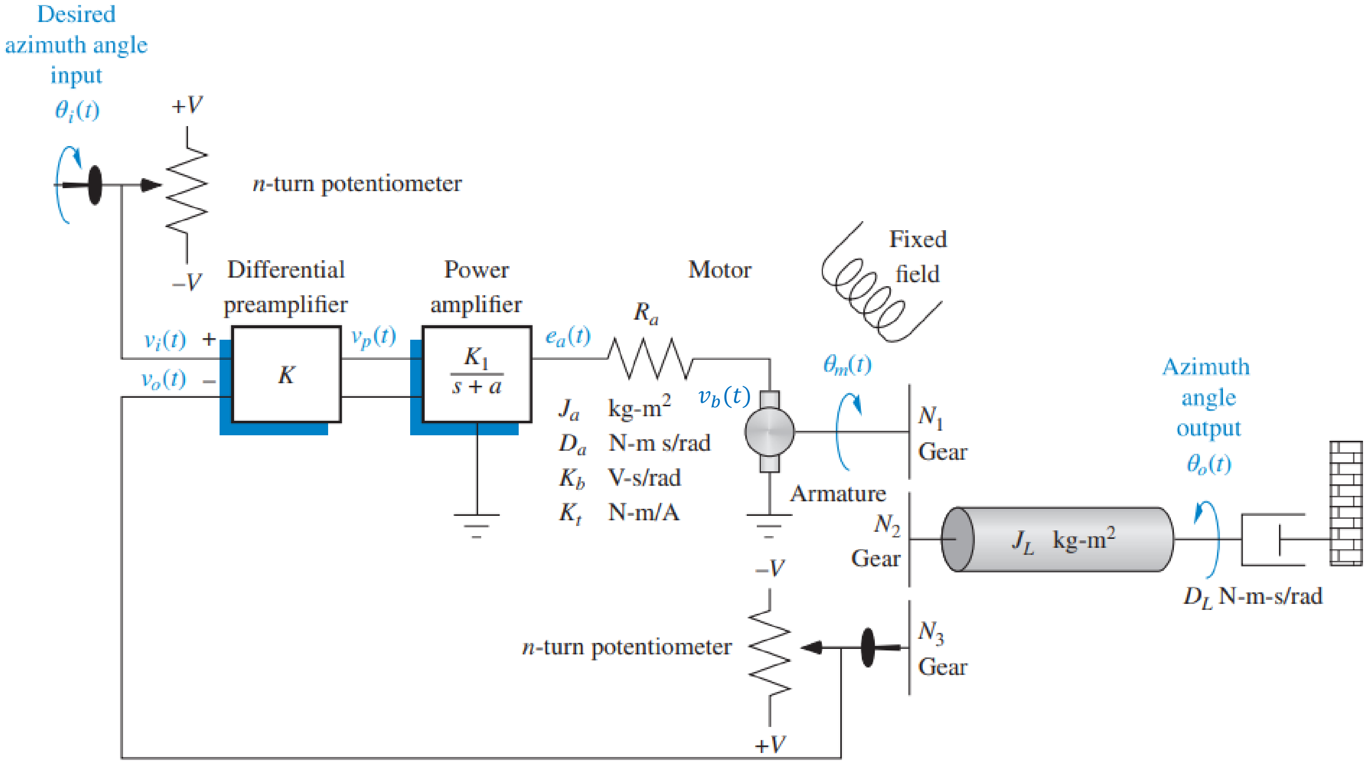
Review of Dynamic System Modeling

❑ Develop a Mathematical Model

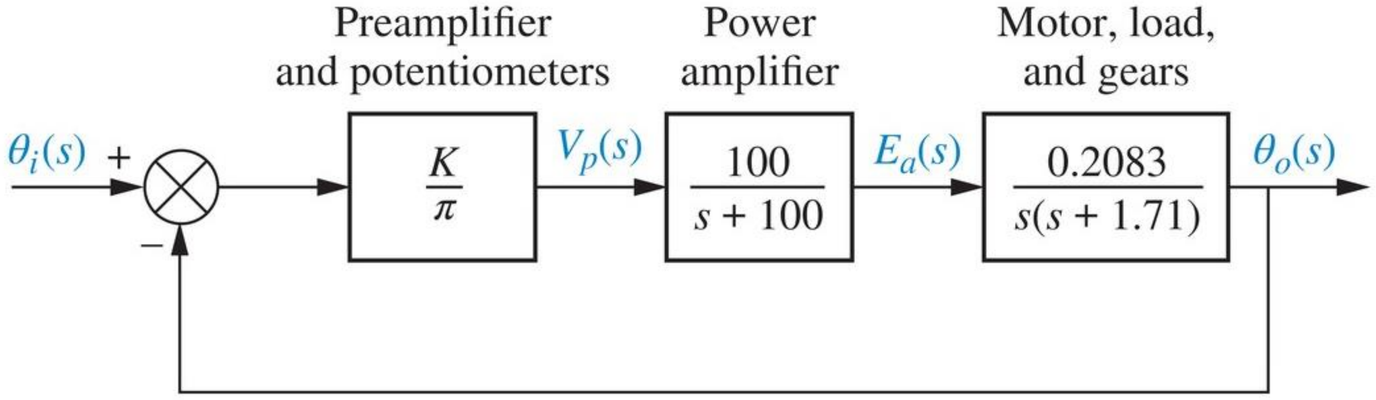
- The results are summarized in the following block diagram.







- The block diagram can be simplified as,



Review of Dynamic System Modeling

System Poles & Transient Response

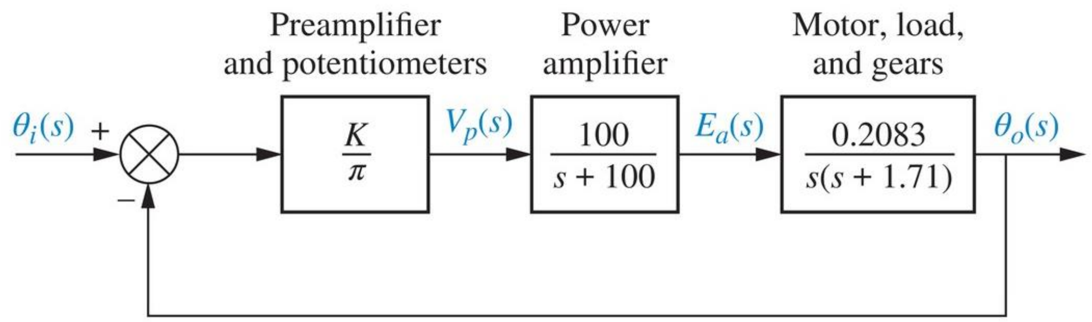
- We know the importance of the poles of a system in determining the transient response.
- The goal is to analyze the open-loop system for angular velocity output.
- The overall open-loop transfer function is:

$$\frac{\Omega_o(s)}{V_p(s)} = \frac{20.83}{(s+100)(s+1.71)}$$

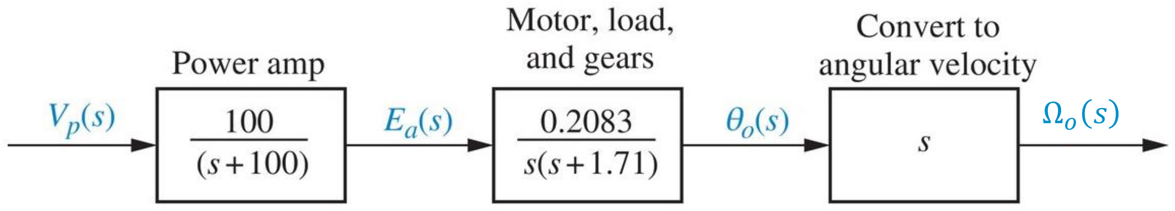
- The open-loop poles are at: $s = -100$ and $s = -1.71$
- Since the system has two negative real poles, the system is overdamped.
- We can also find the damping ratio and the undamped natural frequency.

$$\frac{\Omega_o(s)}{V_p(s)} = \frac{20.83}{s^2 + 101.71s + 171}$$

$$\begin{cases} \omega_n^2 = 171 & \rightarrow \quad \omega_n = \sqrt{171} = 13.08\, rad/s \\ 2\zeta\omega_n = 101.71 & \rightarrow \quad \zeta = 3.89 > 1 \end{cases}$$ Overdamped



Open-loop System



Review of Dynamic System Modeling

❑ System Poles & Transient Response

- We can derive the open-loop angular velocity response of the load to a step-voltage input to the power amplifier, using transfer functions.

- Multiply the open-loop transfer function by a step input $1/s$

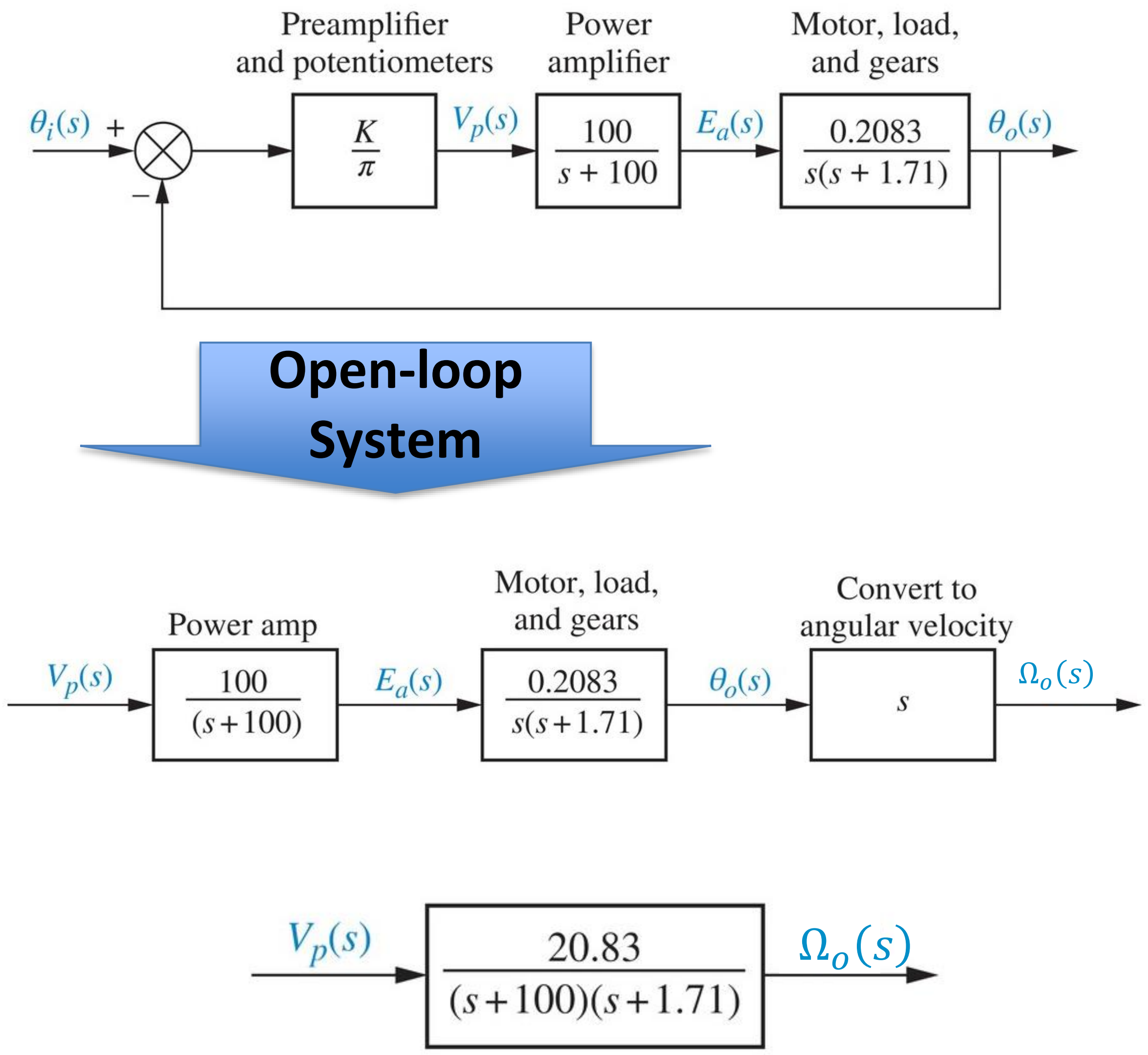
$$\Omega_o(s) = \frac{20.83}{s(s+100)(s+1.71)}$$

- Expanding into partial fractions, we have

$$\Omega_o(s) = \frac{0.122}{s} + \frac{2.12 \times 10^{-3}}{s+100} - \frac{0.124}{s+1.71}$$

- Transforming to the time domain yields the step response:

$$\boxed{\omega_o(s) = 0.122 + (2.12 \times 10^{-3})e^{-100t} - 0.124e^{-1.71t}}$$



Review of Dynamic System Modeling

❑ State-space Model

- We can derive the state-scape model of the open-loop system from its transfer function model.

$$\frac{\Omega_o(s)}{V_p(s)} = \frac{20.83}{s^2 + 101.71s + 171}$$

- Cross-multiplying and taking the inverse Laplace transform with zero initial conditions, we have

$$s^2\Omega_o(s) + 101.71s\Omega_o(s) + 171\Omega_o(s) = 20.83V_p(s)$$

$$\ddot{\omega}_o(t) + 101.71\dot{\omega}_o(t) + 171\omega_o(t) = 20.83v_p(t)$$

- Define the state variables as below and find the state equations and output equation:

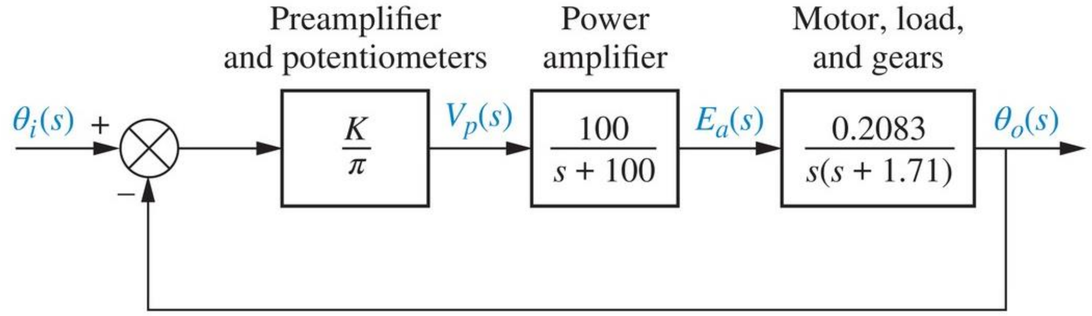
$$q_1 = \omega_o(t) \quad \rightarrow \quad \dot{q}_1 = \dot{\omega}_o(t) \quad \rightarrow \quad \dot{q}_1 = q_2 \qquad \text{Eqn. (1)}$$

$$q_2 = \dot{\omega}_o(t) \quad \rightarrow \quad \dot{q}_2 = \ddot{\omega}_o(t) \quad \rightarrow \quad \dot{q}_2 = -101.71\dot{\omega}_o(t) - 171\omega_o(t) + 20.83v_p(t)$$

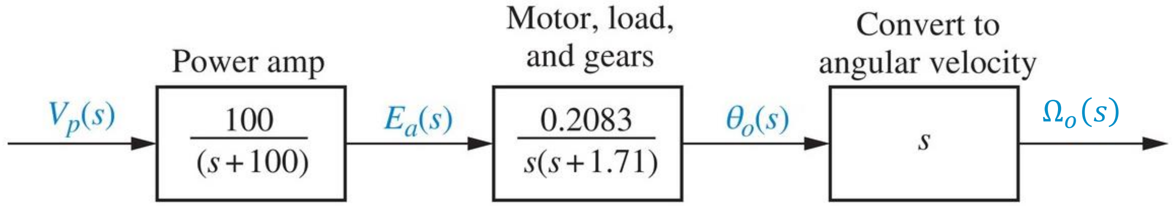
$$\dot{q}_2 = -101.71q_2 - 171q_1 + 20.83v_p(t) \qquad \text{Eqn. (2)}$$

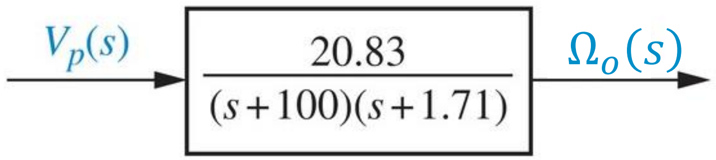
State Equations
$$\begin{cases} \dot{q}_1 = q_2 \\ \dot{q}_2 = -101.71q_2 - 171q_1 + 20.83v_p(t) \end{cases}$$

Output Equation
$$\begin{cases} y(t) = q_1 \end{cases}$$



Open-loop System





Review of Dynamic System Modeling

❑ State-space Model

- The state-scape model of the open-loop system in the matrix-vector form is:

State Equations
$$\begin{cases} \dot{q}_1 = q_2 \\ \dot{q}_2 = -101.71q_2 - 171q_1 + 20.83v_p(t) \end{cases}$$

Output Equation
$$\{\, y(t) = q_1$$

$$\boxed{\dot{\mathbf{q}}(t) = \mathbf{A}\mathbf{q}(t) + \mathbf{B}\mathbf{u}(t)}$$

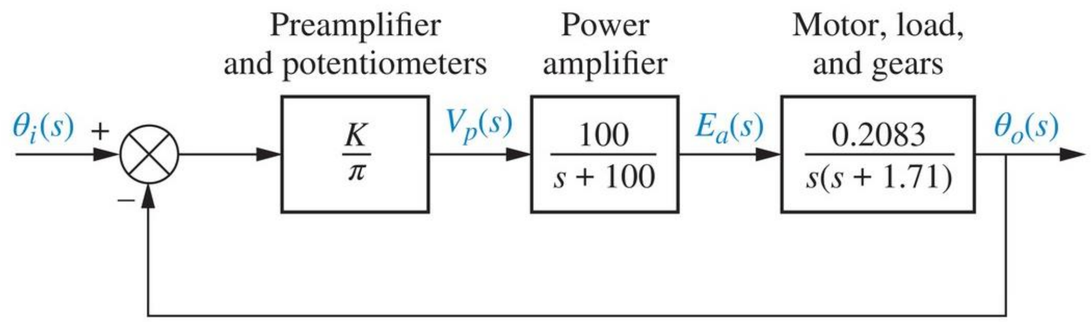
State Equation

$$\rightarrow \begin{bmatrix} \dot{q}_1(t) \\ \dot{q}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -171 & -101.71 \end{bmatrix} \begin{bmatrix} q_1(t) \\ q_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 20.83 \end{bmatrix} v_p(t)$$

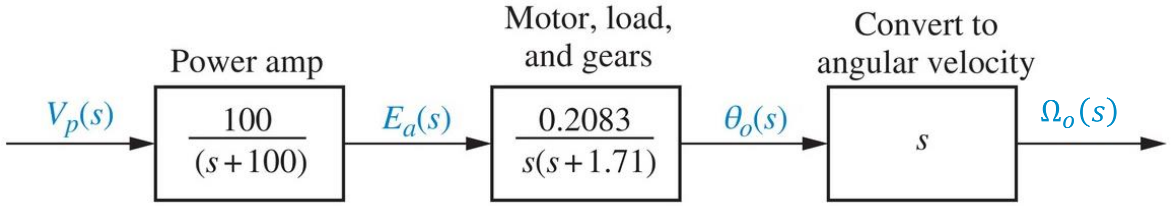
$$\boxed{\mathbf{y}(t) = \mathbf{C}\mathbf{q}(t) + \mathbf{D}\mathbf{u}(t)}$$

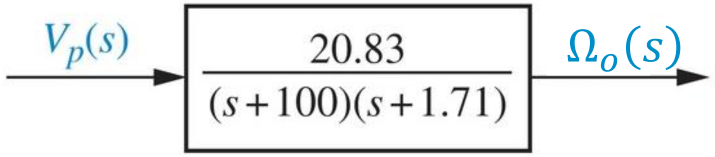
Output Equation

$$\rightarrow y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} q_1(t) \\ q_2(t) \end{bmatrix} + [0]v_p(t)$$



Open-loop System





THANK YOU

HUMBER

WE ARE HUMBER