LAB 1: OPEN-LOOP vs CLOSED-LOOP CONTROL SYSTEMS

Course Number	**MENG 3510**
Course Title	**Control Systems**
Semester/Year	**Winter / 2025**

Lab/Tutorial Report No.	**Lab 1**
Report Title	**Open-loop vs Closed-loop Control Systems**
Section No.	0NA
Group No.	N/A
Submission Date	January 13th 2025
Due Date	January 19th 2025

Student Name	**Signature***	**Total Mark**
Michael McCorkell		**/ 50**

* By signing above, you attest that you have contributed to this submission and confirm that all work you have contributed to this submission is your work. Any suspicion of copying or plagiarism in this work will result in an investigation of Academic Misconduct and may result in a ZERO on the work or possibly more severe penalties.

https://academic-regulations.humber.ca/2021-2022/17.0-ACADEMIC-MISCONDUCT

LAB 1 Grading Sheet

Student First Name: Michael	
Part A: Transfer Function Modeling	**/20**
Part B: Open-loop Control vs Closed-loop Control Approaches	**/25**
General Formatting: **Clarity, Writing style, Grammar, Spelling, Layout of the report**	**/5**
Total Mark	**/50**

LAB 1: OPEN-LOOP vs CLOSED-LOOP CONTROL SYSTEMS

OBJECTIVES

- To get familiar with the MATLAB and Simulink environments
- To learn how to simulate system models in Simulink
- To understand some of the basic concepts of open-loop and closed-loop systems

DISCUSSIONS OF FUNDAMENTALS

SYSTEM MODELING

Consider the following **Single-Tank System** as shown below:

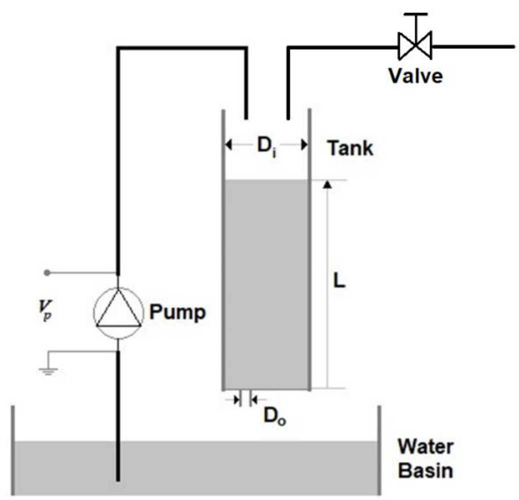


Figure 1: Single-Tank System

The **Single-Tank system** consists of a ***pump*** with a ***water basin*** and a ***tank***. The pump drives the water vertically from the bottom water basin up to the top of the system. The flow from the tank flows through an outlet ***orifice*** located at the bottom of the tank into the main water reservoir. Liquid level control is common in many industries, such as pulp and paper mills, petrochemical plants and water treatment facilities.

The rate of flow can be changed by changing the voltage of the pump (V_p) and/or by using outflow orifices with different diameters. Here, the voltage to the pump (V_p) is considered as the input to the process and the water level in the tank (L) is the output of the system. There exists a ***valve*** to divert extra water into the Tank. In this process the valve position (ON/OFF) is considered as a disturbance to the process.

The parameters of the Single-Tank system are defined as follows:

V_p: Voltage to the pump ($0V \leq V_p \leq 100V$)
D_i: Tank inside diameter (30 cm)
D_o: Out flow orifice diameter ($1\ cm$)
L: The water level in the tank
v: The valve position ($v = 1$ is ON, $v = 0$ is OFF)

Applying the mass balance principle to the water level in the Tank, the ***equation of motion*** of the water level Is derived as:

$$A\frac{dL(t)}{dt} = F_i(t) - F_o(t)$$

where, $A = \pi D_i^2/4$ is the ***area of the Tank***, F_i and F_o are the volumetric ***inflow rates*** and ***outflow rates*** of the Tank, respectively. Assume that the volumetric ***inflow rate*** into the Tank is directly proportional to the applied pump voltage:

$$F_i(t) = K_p V_p(t)$$

where, K_p is the ***pump flow constant***. Applying the Bernoulli's equation for small orifices, the ***outflow velocity*** from Tank can be expresses by the following relationship,

$$v_o(t) = \sqrt{2gL(t)}$$

Lastly, the volumetric ***outflow rate*** from Tank can be expressed as below:

$$F_o(t) = A_o v_o(t)$$

where, $A_o = \pi D_o^2/4$ is the ***outlet area of Tank***.

Therefore, the **nonlinear differential equation model** of dynamic system is obtained as:

$$A\frac{dL(t)}{dt} = K_p V_p(t) - A_o\sqrt{2gL(t)}$$

The ***disturbance valve*** position is also added to the model with the constant flow rate of $K_d = 0.1$. The **Transport Delay** block enables us to apply the disturbance at the desired time.

The **nonlinear** model of the Single-Tank System can be modeled in Simulink as Figure 2.

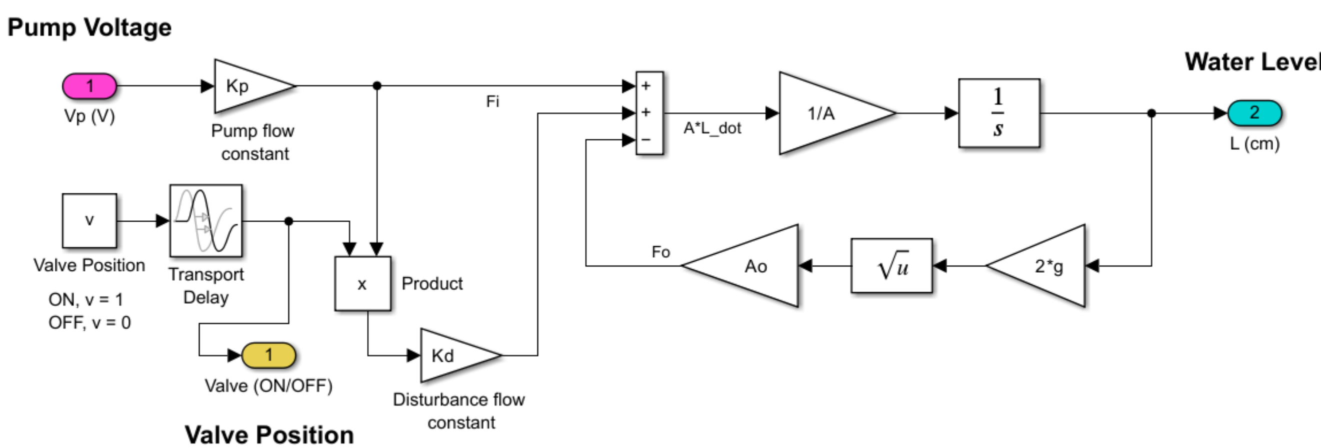


Figure 2: Simulink block diagram of Single-Tank System

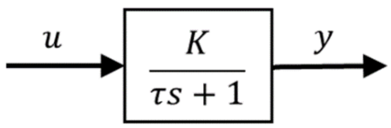
Here, the ***pump voltage*** (V_p) is considered as the <u>**input**</u> to the process and the ***water level*** in the tank (L) is the <u>**output**</u> of the system. There exists a ***valve*** to divert extra water into the Tank. In this process the ***valve position*** (ON/OFF) is considered as a disturbance to the process.

TRANSFER FUNCTION IDENTIFICATION FROM STEP RESPONSE

The water level dynamics can be modeled using a **first-order** transfer function:

$$\frac{Y(s)}{U(s)} = \frac{K}{\tau s + 1}$$

where K is called the **steady-state gain**, or **DC gain**, and τ is the **time constant** of the system. In this case, the output, y, is **water level** of the tank and the input, u, is the **voltage** applied to the pump.



For example, the step response shown in Figure 3 was generated using for a system with the steady-state gain and time constant parameters with $K = 5$ rad/s/V and $\tau = 0.05$ s.

The step input begins at time t_0.

The input signal has a minimum value of u_{min} and a maximum value of u_{max}.

The output signal starts initially at y_0 and once the step is applied, the output settles to a steady-state value of y_{ss}.

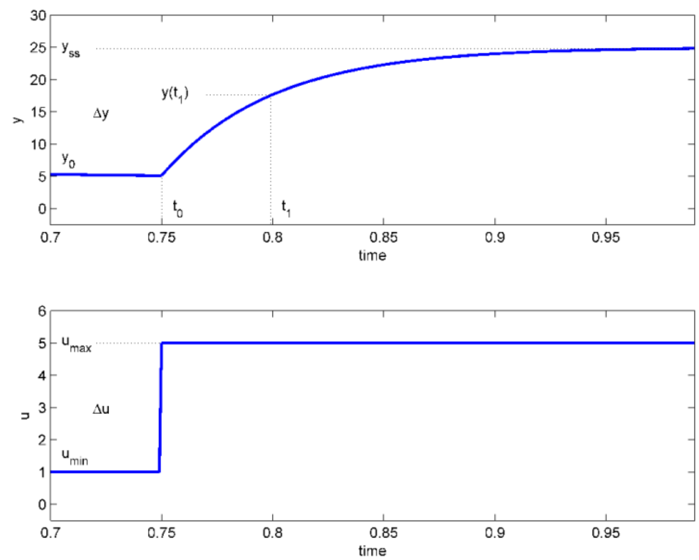


Figure 3 - Step response of system with K=5 and τ =0.05.

The **steady-state gain** can be used to determine the output of the system once it has reached steady-state conditions for a given input signal. It can be found from the input and output signals of the response as follows:

$$K = \frac{\Delta y}{\Delta u} \tag{10}$$

where $\Delta y = y_{ss} - y_0$ is the difference between the steady-state and initial output of the system, and $\Delta u = u_{max} - u_{min}$ is the amplitude of the step input.

The **time constant** characterizes the system's transient response and is defined as the time it takes for the output of the system to reach 63.2% of its steady-state output. It shows how fast the system responds to an applied input. The time constant can be determined from the output response as follows:

$$\tau = t_1 - t_0 \tag{11}$$

where t_0 is the time when the input is applied to the system and t_1 is the time at which the system output reaches 63.2% of its steady-state output, or $y(t_1) = (1 - e^{-1})\Delta y + y_0 = 0.632\Delta y + y_0$, as illustrated in Figure 3.

PART 1: Transfer Function Model

Dynamic models are essential for understanding the system behavior and design control systems. These models can either be derived mathematically from the first principles of physics of process or empirically from the collected input-output data from the process. The purpose of this part is to obtain a **transfer function model** of the Single-Tank system ***experimentally*** from the step response.

1. Create the following open-loop system in Simulink, using the provided **Single-Tank System** block. You can find the required blocks as below,

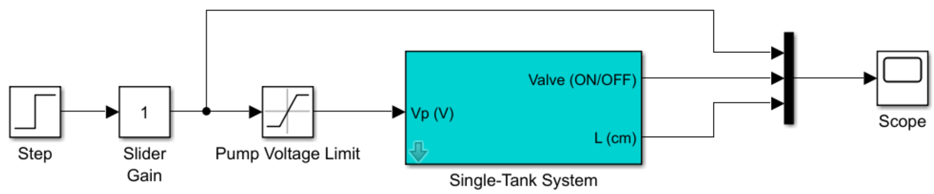
   Simulink > Sources > Step

   Simulink > Math Operations > Slider Gain

   Simulink > Discontinuities > Saturation

   Simulink > Signal Routing > Mux

   Simulink > Sink > Scope

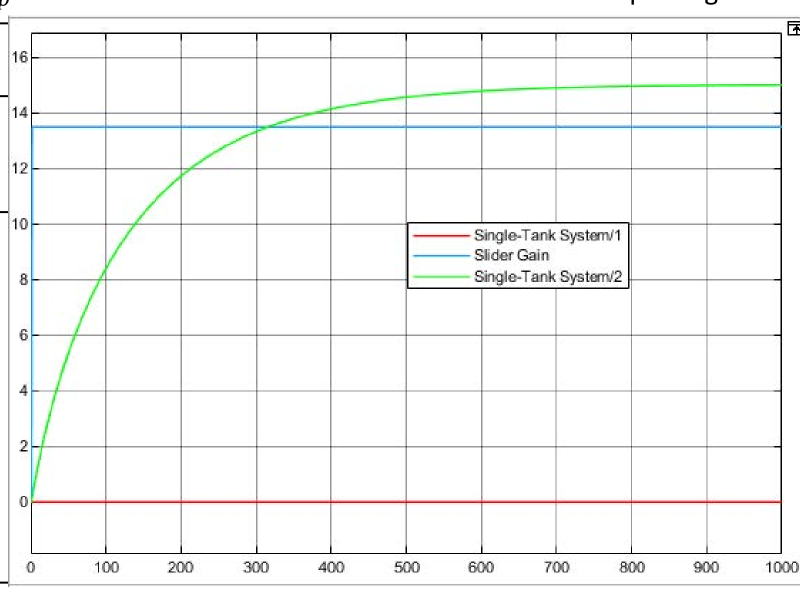


2. Set the **Slider Gain** range to **low = 0** and **high = 20**.
3. Set the **Pump Voltage Limits** to **0** and **100V**.
4. Double-click on the **Single-Tank System** block and set up the parameters based on the given nominal values.
5. Set the disturbance valve position as **OFF** ($v = 0$). Do **not** change the Disturbance Time.
6. **Save** the Simulink model as **Lab1_Part1.slx**.
7. Apply the unit-step signal as the input. Set **Stop time** to **1000 seconds**. **Run** the simulation.
8. Open the **Scope** block to see the pump voltage, water level, and the valve position graphs.
9. Assume that the *desired water level* under the operation condition is *15 cm*. Tune the **Slider Gain** and determine the required input voltage V_p to set the water level at $L = 15\ cm$. Provide the required gain value.

13.5

10. Provide the scope plot below:

Pump Voltage (V) & Water Level (cm)



11. Determine a **first-order transfer function** model for the system based on the step response of the system.

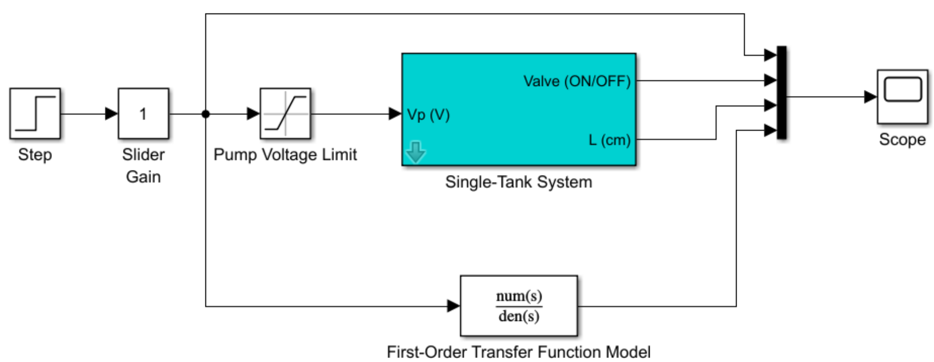
$$G(s) = \frac{K}{\tau s + 1}$$

Find the **DC gain** K and the **time constant** τ from the step response plot and determine the **transfer function** model. You can use the **Scope Cursor Measurement** tools to read the steady-state value and time values. Complete Table 1 based on the calculated values.

Table 1

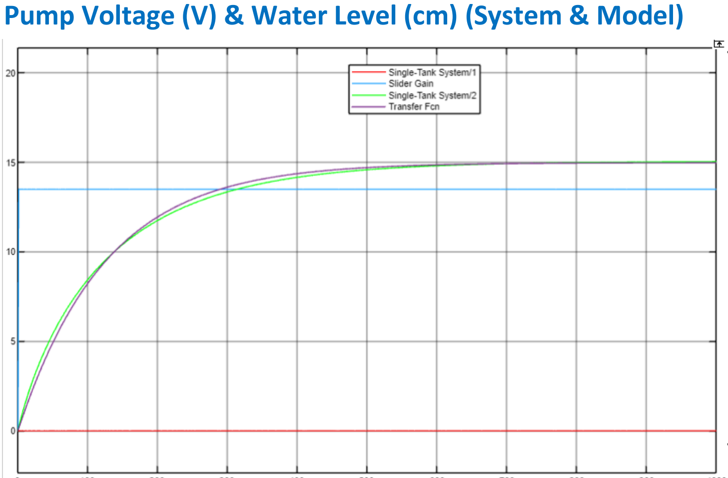
Desired Water Level (cm)	Applied Voltage (V)	Time Constant (sec)	DC-gain (cm/V)	Transfer Function Model G(s)
15 cm	13.5 V	125.1 sec	1.11 cm/V	$G(s) = \frac{1.11}{125.1s + 1}$

12. To verify the identified transfer function model, modify the Simulink model by adding a **Transfer Fcn** block with the identified transfer function model as shown below. You can find the **Transfer Fcn** block in **Simulink** > **Continuous** library.



13. **Run** the Simulink model. Open the **Scope** block and provide the scopes plots.

Pump Voltage (V) & Water Level (cm) (System & Model)



14. Based on the simulation results, did you derive the model parameters correctly?

Yes ✓ **No**

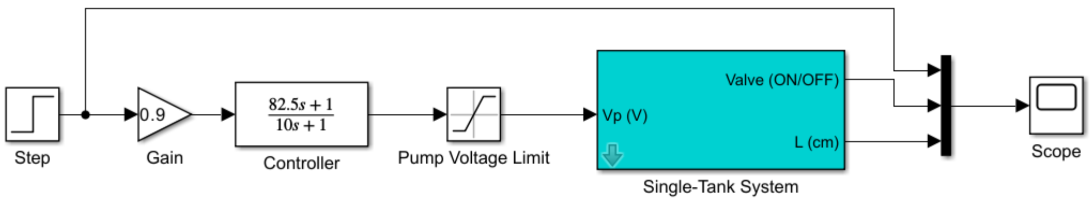
PART 2: Open-loop vs Closed-loop Control Approaches

Control systems are designed to achieve a good performance (accuracy and fast response) by maintaining the stability and robustness of the system. The purpose of this part is to compare the **open-loop control** and **closed-loop control** approaches. Based on the step response observations from Part 1, the main issue of the Single-Tank System is its ***slow dynamics*** and ***large time constant***. Therefore, we assign the following performance criteria.

The speed of the response ***at least 10 times*** faster, the steady-state error **less than 5%**.

1. OPEN-LOOP CONTROL APPROACH

Consider the Simulink diagram of the **Single-Tank System** from Part 1. **Save** the model as **Lab1_Part2A.slx** and modify your model by adding the **Gain** and **Transfer Fcn** blocks to generate the following **Open-loop Control** structure.



15. Set the **Final value** of the step input to **15**, which represents the ***desired water level*** in the tank $L = 15\ cm$.
16. Set the simulation **Stop time** to **150 seconds. Run** the simulation.
17. Open the **Scope** block and calculate the **time constant** and **steady-state error** of the step response. Provide the values in **Table 2**.
18. Based on the simulation results, did the applied controller satisfy the desired speed and accuracy?

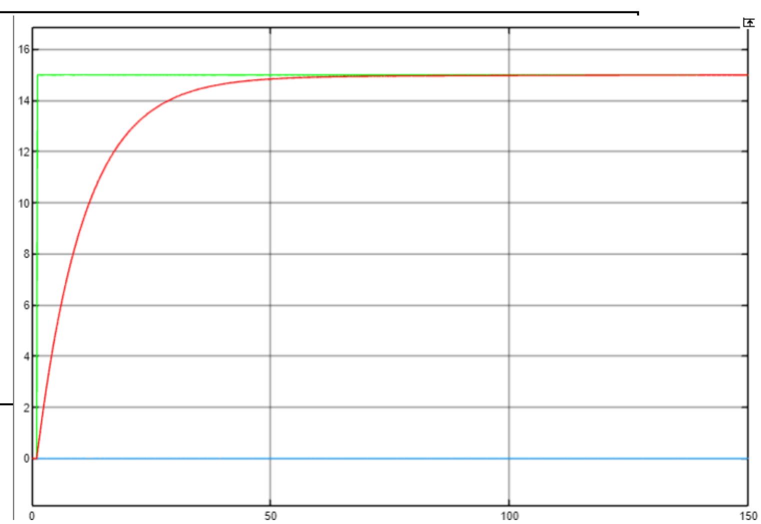
Yes **No** ✓

Table 2

Control Approach	Time Constant (sec)	Steady-State Error (%) = $\frac{desired\ value - actual\ value}{desirde\ value} \times 100\%$
Open-loop Control	10.977 sec	37%

19. Provide the scope plots below.

Desired Water Level & System Output - Open-loop Control



SENSITIVITY & ROBUSTNESS TEST

At this step we will check the **sensitivity** and **robustness** of the **Open-loop Control** approach to the change in the ***system parameters*** and the ***external disturbance***.

20. Double-click on the **Single-Tank System** block and change the **Tank Outflow Orifice Diameter** to **0.95 cm**.
21. Set the simulation **Stop time** to **1000 seconds. Run** the simulation.
22. Open the **Scope** block and observe the effect of changing the system parameter on the water level. What is the final level of water?

18.5

23. Did the controller maintain the water level close to the desired level by less than 5% steady-state error?

Yes **No** ✓ it had a -23% -> 23%

24. Set back the **Tank Outflow Orifice Diameter** to the original value **1 cm**.

25. Double-click on the **Single-Tank System** block and set the **Disturbance Time** to **150 seconds**. Set the disturbance valve position to **ON** ($v = 1$).
26. **Run** the simulation for **1000 seconds**.
27. Open the **Scope** block and observe the effect of adding disturbance on the water level. What is the final level of water after opening the disturbance valve?

18.2

28. Did the controller maintain the water level close to the desired level by less than 5% steady-state error?

Yes **No** ✓ it had a -21% -> 21%

29. What is your conclusion on the **sensitivity** and **robustness** of **Open-loop Control Approach**? Justify your answer. Discuss disadvantages of having no feedback in the open-loop control system.

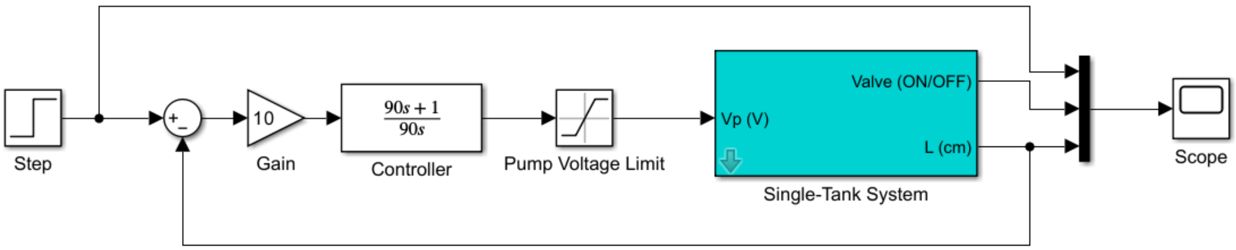
The results acquired indicate that system is highly sensitive to disturbances and parameter changes, as shown in the above tests. Where both didn't have a 5% steady state error.

My justification is that the controller doesn't have a mechanism to measure the actual output to compare the desired set point. And with the tests above it shows that the mechanism cannot adapt to variations or recover from disturbances.

Disadvantages are that it can correct errors, very sensitive to disturbances.

2. CLOSED-LOOP CONTROL APPROACH

Consider the Simulink diagram of the **Single-Tank System** from the previous step. **Save** the model as **Lab1_Part2B.slx** and modify your model to generate the following **Closed-loop Control** structure with **feedback**.



30. Set the **Final value** of the step input to **15**, which represents the ***desired water level*** in the tank $L = 15\ cm$.
31. Set the simulation **Stop time** to **150 seconds. Run** the simulation.
32. Open the **Scope** block and calculate the **time constant** and **steady-state error** of the step response. Provide the values in **Table 3**.
33. Based on the simulation results, did the applied controller satisfy the desired speed and accuracy?

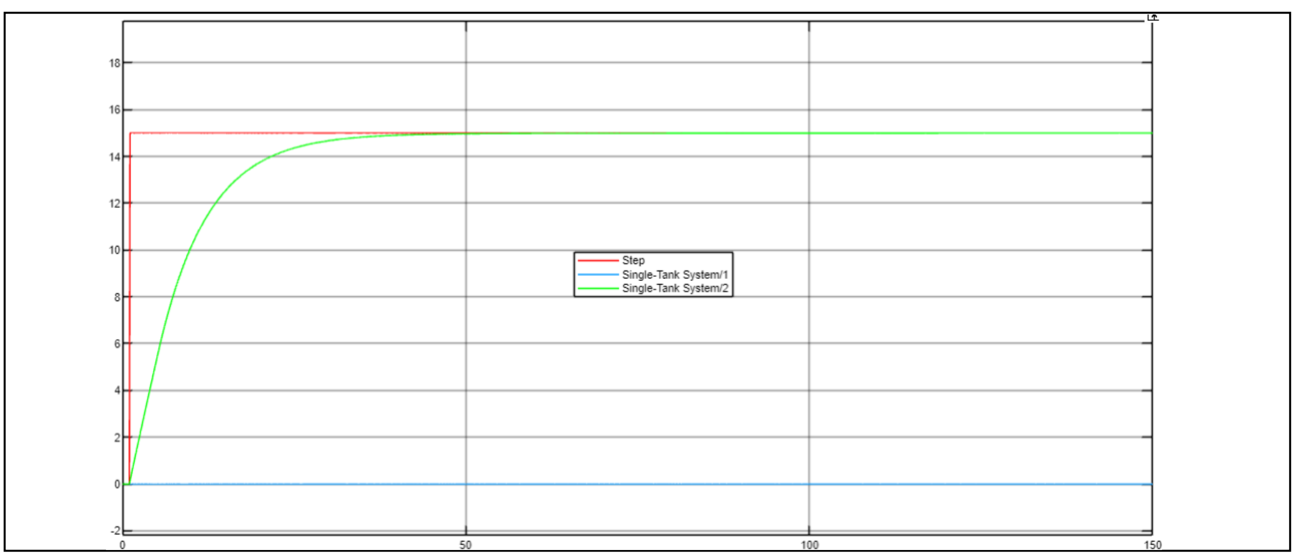
Yes✓ **No**

Table 3

Control Approach	Time Constant (sec)	Steady-State Error (%) = $\frac{\textit{desired value} - \textit{actual value}}{\textit{desirde value}} \times 100\%$
Closed-loop Control	90 sec	0.053%

34. Provide the scope plots below.

Desired Water Level & System Output - Closed-loop Control



SENSITIVITY & ROBUSTNESS TEST

At this step we will check the **sensitivity** and **robustness** of the **Closed-loop Control** approach to the change in the ***system parameters*** and the ***external disturbance***.

35. Double-click on the **Single-Tank System** block and change the **Tank Outflow Orifice Diameter** to **0.95 cm**.
36. Set the simulation **Stop time** to **1000 seconds. Run** the simulation.
37. Open the **Scope** block and observe the effect of changing the system parameter on the water level. What is the final level of water?

15 cm

38. Did the controller maintain the water level close to the desired level by less than 5% steady-state error?

Yes ✓ **No**

39. Set back the **Tank Outflow Orifice Diameter** to the original value **1 cm**.

40. Double-click on the **Single-Tank System** block and set the **Disturbance Time** to **150 seconds**. Set the disturbance valve position to **ON** ($v = 1$).
41. **Run** the simulation for **1000 seconds**.
42. Open the **Scope** block and observe the effect of adding disturbance on the water level. What is the final level of water after opening the disturbance valve?

15 cm

43. Did the controller maintain the water level close to the desired level by less than 5% steady-state error?

Yes ✓ **No**

44. What is your conclusion on the **sensitivity** and **robustness** of **Closed-loop Control Approach**? Justify your answer. Discuss the advantages of having **feedback** in this approach.

The results acquired indicate that system is controlled with Error correction, or feedback, where the desired water level is acquired.

My justification is that the system is error correction or that the controller and gain is minimizing the disturbances.

Advantages are that it is outputting a Steady-state error less than 5%. Which means that it's very close to our desired water level.