Comparison of Performance Analysis of PD-FLC in Controlling and Monitoring Water Level in the Tank with SISO-FLC and MISO-FLC

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ABSTRACT – In this study, three different techniques for controlling water levels in a tank are compared: the single-input single-output (SISO) fuzzy logic controller (FLC), the multiple-input single-output (MISO) FLC, and the proportional-derivative (PD)-FLC. By conducting simulations using MATLAB/Simulink, it was discovered that the PD-FLC approach outperformed the other two techniques in various aspects. Specifically, the PD-FLC method demonstrated a superior response time, enabling it to quickly adapt to changes in water levels and maintain the desired level effectively. Moreover, the execution speed of the PD-FLC technique was excellent, as it efficiently processed input variables and provided precise control signals to ensure smooth water level control. One notable advantage of the PD-FLC approach was its ability to prevent overshooting, which can cause instability and inefficiency in control systems. By effectively maintaining stable water level control without overshooting the desired setpoint, the PD-FLC technique proved to be highly efficient in this study.

1. Introduction

Water level control is an essential process in various industrial and residential applications. To ensure efficient and accurate control, different control techniques have been proposed and employed. Two widely used control approaches for water level control are fuzzy logic control and PID (Proportional-Integral-Derivative) control [1] [2].Fuzzy logic control, as the name implies, utilizes fuzzy sets and linguistic variables to represent and handle uncertainty. This control technique demonstrates its effectiveness in dealing with complex systems with nonlinear dynamics, such as water level control systems [1]. By incorporating expert knowledge and experience into the control system, fuzzy logic control can adapt and respond to changing conditions, guaranteeing precise and stable water level regulation [3]

On the other hand, PID control is a classical control strategy that has proven its efficiency in numerous applications, including water level control. The PID controller adjusts the control signal based on the error between the desired set point and the actual water level, employing proportional, integral, and derivative actions [4]. This feedback-driven approach provides robustness and stability to the control loop, ensuring accurate and timely regulation of the water level [5] [6].

Both fuzzy logic control and PID control have their own strengths and limitations. While fuzzy logic control excels in handling complex and uncertain systems, PID control offers a well-established and widely understood control methodology [11] [13]. Therefore, combining these two control approaches can potentially enhance the performance of water level control systems, allowing for superior regulation accuracy and robustness.

In this study, we target to design and implement a single water level control system using a combination of fuzzy logic control and PD control. In addition to analyze the use of the fuzzy logic approach in regulating and sustaining the water level at a fixed value in a solitary tank under different circumstances. These circumstances comprise single input-single output (SISO), multi input single output (MISO), and PD-like fuzzy logic control (FLC). Furthermore, the intention is to assess and contrast the system's response characteristics in each condition, encompassing parameters such as rise time, settling time, and peak magnitude.

2. Fuzzy Logic Control System.

Fuzzy logic control system is a type of control system that uses the principles of fuzzy logic to make decisions and control processes. Fuzzy logic is a mathematical approach that deals with uncertainty and imprecision, allowing for the representation and manipulation of vague and subjective information [12]. In a fuzzy logic control system, the inputs and outputs are represented as fuzzy sets, where each set represents a range or degree of membership in a particular category. The control rules are defined using linguistic variables and fuzzy IF-THEN rules. These rules describe how the inputs should be mapped to the outputs based on fuzzy logic reasoning [12].

The key advantage of fuzzy logic control systems is their ability to handle and process uncertain, imprecise, or incomplete information. This makes them particularly useful in systems where there are multiple variables involved and where the relationships between these variables are difficult to define precisely. Fuzzy logic control systems are often used in applications such as robotics, traffic control, and industrial processes. Overall, fuzzy logic control systems provide a flexible and intuitive approach to control, allowing for the incorporation of human-like decision-making processes into automated systems.

2.1 Basic Configuration of a Fuzzy Logic Control System

Figure 1 illustrates a fuzzy logic control system. It consists of four main components:

1. Fuzzifier: The fuzzifier receives crisp inputs from the system and converts them into fuzzy sets using membership functions. Membership functions define the degree of membership of each input value to a particular linguistic variable (such as low, medium, or high).

2. Rule Base: The rule base contains a set of if-then rules that describe the behavior of the system. Each rule consists of antecedents (inputs) and consequents (outputs). The antecedents are defined using the linguistic variables and membership functions from the fuzzifier.

3. Inference Engine: The inference engine applies the rules from the rule base to determine the appropriate action to take based on the current inputs. It combines the outputs of the rules using operators such as AND, OR, and NOT to generate a final output.

4. Defuzzifier: The defuzzifier converts the fuzzy output from the inference engine back into a crisp output value. It uses the membership functions associated with the output linguistic variables to determine the crisp output value

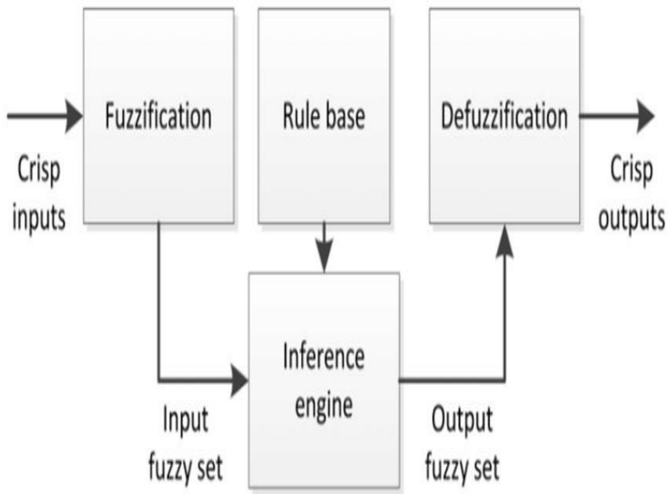


Figure 1: Fuzzy Logic controller block diagram [14]

3. Single Tank Level Control System.

Figure 2 illustrates the system of a single-tank water level, which includes a pipeline, valve, water tank, and liquid level sensor. In the dynamic operating state, water continually flows into and out of the tank. The opening of the regulating valve controls the water inflow **qin(t)**, and the water level in the tank **h(t)** represents the balance of water **qin(t)** and outflow **qout(t)**. The water level **h(t)** is measured using the level sensor. The purpose of the tank water level control system is to overcome all interference factors and maintain a constant water level [7] [8].

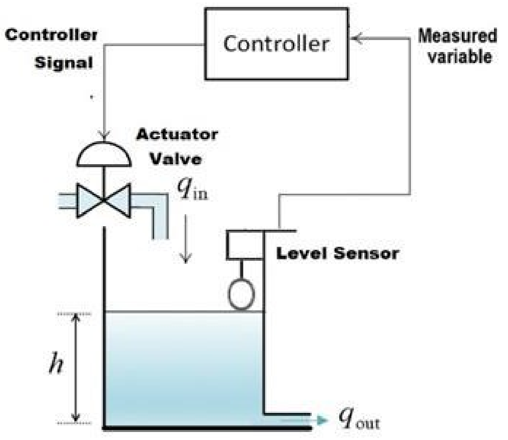


Figure 2: Schematic diagram of single tank level control system

The mathematical representation of the tank system model involves the relationship between the incoming flow of the tank $\mathbf{q_{in}(t)}$ and the outgoing flow $\mathbf{q_{out}(t)}$ through the drainage pipe. This relationship can be expressed through the balance flows equation.

$$q_{in}(t) - q_{out}(t) = A\frac{dh(t)}{dt} \qquad (1)$$

The level water of the tank is the integration of the equ(1)

$$h(t) = \int \frac{1}{A} \left(q_{in}(t) - q_{out}(t)\right) \qquad (2)$$

$$q_{out}(t) = a * \sqrt{2gh(t)} \qquad (3)$$

Where h(t) represents the water level, $\mathbf{q_{in}(t)}$ denotes the input flow, A is the cross-sectional area of the tank, a is the cross-sectional area of the pipe, and $\mathbf{g = 9.8m/sec^2}$ represents the acceleration due to gravity. Applying Laplace Transform for equ(2)

$$H(s) = \frac{1}{S} * \frac{1}{A} \left(Q_{in}(s) - Q_{out}(s)\right) \qquad (4)$$

$$H(s) = E(s) * \frac{1}{A} * \frac{1}{S} \qquad (5)$$

The Figure 2 illustrates the mathematical block diagram

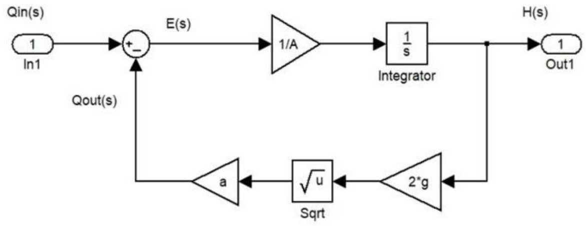


Figure 3: Simulink diagram of equ(4)

An integrator with saturation block is used in control systems engineering to model the behavior of a valve used for controlling water flowing into a tank, the integrator with saturation block can model the dynamics of the valve and its response to various inputs. In this representation, the integrator captures the cumulative effect of the water flow over time and produces an output that is proportional to the integral of the input signal. This helps in maintaining a desired water level in the tank. The saturation block is used to incorporate the physical limitations of the valve. valve has certain operating limits and cannot output flow rates beyond those limits. The saturation block ensures that the output of the integrator remains within these limits, preventing issues such as overflow or excessive flow. By combining the integrator and saturation block, the control system can accurately regulate the water flow into the tank, despite disturbances or changes in the input signal [9][13]. The block diagram of valve is represented in Figure 4.

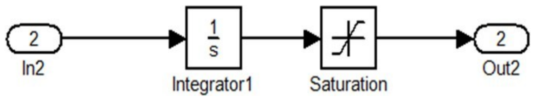


Figure 4: The Simulink diagram of the valve

4. Design Methodology

The objective of this paper is to examine the fuzzy logic approach for controlling and maintaining the water level at a specific value in a single tank under various conditions, namely: single input-single output (SISO), multi input single output (MISO), and PD-like fuzzy logic control (FLC). Additionally, it aims to compare the response attributes of the system in each condition, including rise time, settling time, and peak magnitude.

4.1 Single Input-Single Output Fuzzy Logic Control (SISO FLC)

A SISO FLC system is a kind of control system that utilizes fuzzy logic to derive decisions from a single input and generate a single output. In this system, the input variable usually corresponds to a continuous value indicative of the water level. Figure 5 illustrates the SISO FLC system designed for a Mamdani type fuzzy controller.

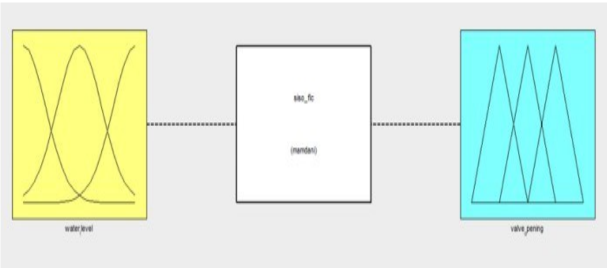


Figure 5: the SISO FLC system for Mamdani type

The input, denoted as "water level", refers to the water level in the tank. This input is applied to the rule editor [6]. According to the rules written in the rule editor, the controller takes action and governs the opening of the valve. The output of the controller is denoted by "valve opening".The Mamdani type fuzzy controller uses a rule base expressed in linguistic terms. In the SISO FLC system, the fuzzy set is configured with three levels for both inputs and outputs: Figure 6 illustrates the membership functions of the fuzzy set that characterize the input as "Low," "Desired," and "High" within the range of **h(t) ∈ [0,15].**

Figure 6: fuzzification of the input water level h(t)

Figure 7 illustrates the membership functions of the fuzzy set that characterize the output as " Close_fast," " No_change," and " Open_fast " within the range of **u(t) ∈ [- 40 to 40].**

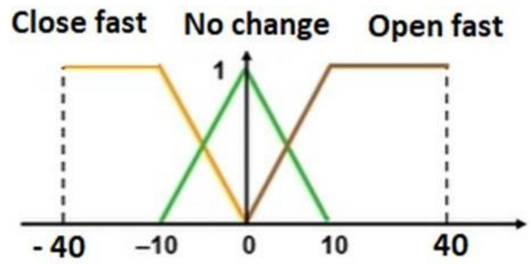
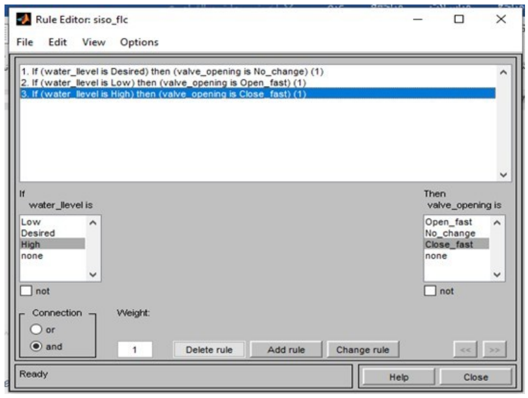


Figure 7: fuzzification of the output "valve opening" for SISO FLC

4.1.1 Fuzzy Rules of The SISO FLC

These rules are typically expressed in the form of "If [input is A] then [output is B]." The number of rules depends on the complexity of the system and the number of linguistic terms. After fuzzification, the next step is to create a rule base. The rule base is composed of the following three rules.

1. If (water_level is Desired) THEN (valve_opening is No change)
2. If (water_level is Low) THEN (valve_opening is Open_fast)
3. If (water_level is High) THEN (valve_opening is Closed_fast)



4.1.2 Simulink Block Diagram of The SISO FLC

Figure 9 shows the Simulink block diagram of the of the SISO FLC. The fuzzy inference system is implemented in this fuzzy logic controller and simulated to get the response of the SISO FLC to the given parameters. Values of the parameters are given as a= 0.015m2, A=0.5m2, qin(Max) = 0.025m3/sec, g = 9.8m/sec2.

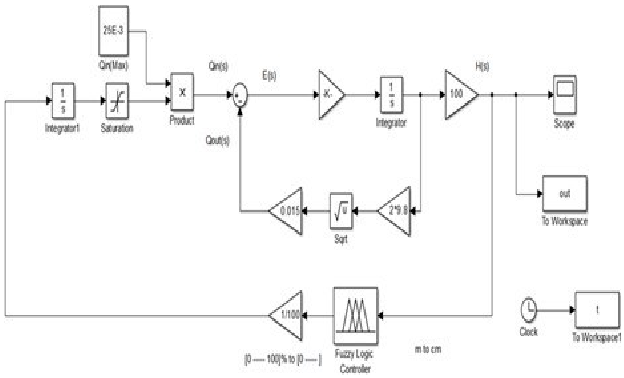


Figure 9: Simulink diagram of the SISO FLC system

4.2 Multi Input-Single Output Fuzzy Logic Control (MISO FLC)

A multi-input single-output fuzzy logic control system is a control system that employs the principles of fuzzy logic to arrive at decisions by considering several input variables and generating a single output. This type of control system incorporates linguistic rules to combine the input variables and their respective membership functions. In this particular case, the system involves two inputs: water level **h(t)** and the rate of change of water level $\frac{dh(t)}{dt}$ The output parameter is the valve opening signal **u(t).** The configuration depicted in Figure 10 depicts a MISO FLC (Multi-Input Single-Output Fuzzy Logic Control) system using a Mamdani-type fuzzy controller.

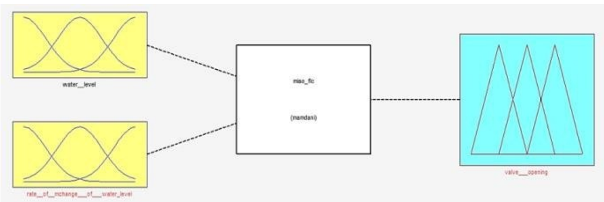


Figure 10: the MISO FLC system for Mamdani type

The inputs, denoted as "water level" and " rate of change of water level. These inputs are applied to the rule editor. According to the rules written in the rule editor, the controller takes action and governs the opening of the valve. The output of the controller is denoted by "valve opening".The fuzzy set is configured for two inputs and an output. Figure 6 illustrates the membership functions of the fuzzy set for the first input "water level", which are characterized as "low," "desired," and "high" within the range of **h(t)** $\in$ **[0, 15].** On the other hand, Figure 11 illustrates the membership functions of the fuzzy set that characterize the second input "rate of change of water level" as three levels "Negative," "Zero," and "Positive" within the range of $\frac{dh(t)}{dt}$ $\in$ [-5, 5].

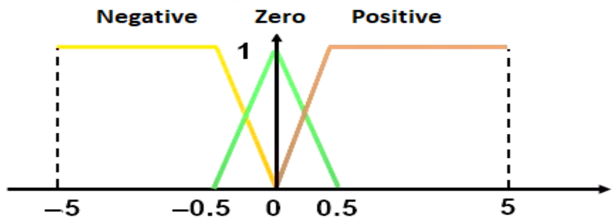


Figure 11: fuzzification of the second input "rate of change of water level"

The fuzzy logic control system combines variables of the first input, "water level," the second input, "rate of change of water level," and their membership functions, with respect to the rule editor, to produce a single output, "valve opening," as shown in Figure 12

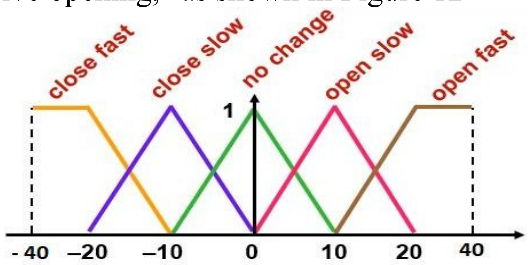


Figure 12: fuzzification of the output "valve opening" for MISO FLC

Figure 12 illustrates the membership functions of the fuzzy set that characterize the single output " valve opening " as five levels "Close_fast," "Close_slow," " No_change," and " Open_fast " " Open_slow " within the range of **u(t)** $\in$ [-40 to 40].

4.2.1 Fuzzy Rules of The MISO FLC

Once the process of fuzzification is complete, the subsequent step involves constructing a rule base comprising of the following five rules.

1. If (water_level is Desired) THEN (valve_opening is No change)
2. If (water_level is Low) THEN (valve_opening is Open_fast)
3. If (water_level is High) THEN (valve_opening is Closed_fast)

4. If (water_level is Desired) AND (rate of change of water level is Negative) THEN (valve_opening is Open_slow)
5. If (water_level is Desired) AND (rate of change of water level is Positive) THEN (valve_opening is Close_slow)

4.2.2 Simulink Block Diagram of The MISO FLC

The block diagram in figure 9 was developed to be compatible with the conditions of MISO FLC, where the fuzzy logic controller input was modified to have two inputs. The first input is the water level in the tank, and the second input is the rate of change in the water level. The second input is represented by the derivative block shown in Figure 13.

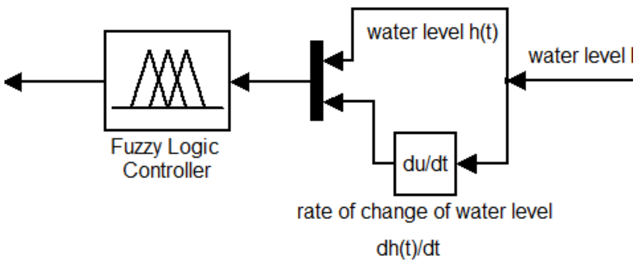


Figure 13: Fuzzy logic controller inputs for MISO

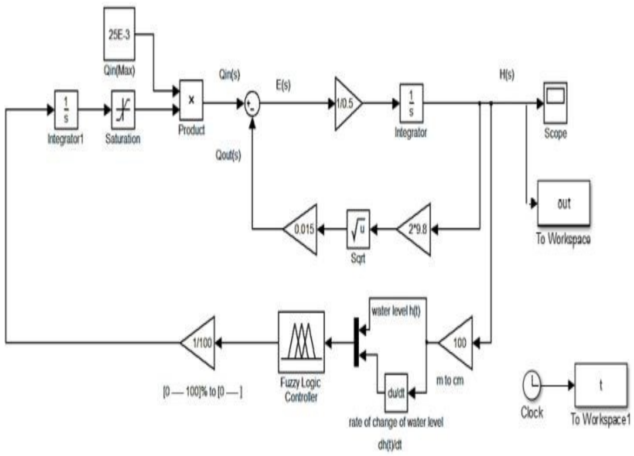


Figure 14: Simulink diagram of the MISO FLC system

4.3 Proportional derivative - fuzzy logic control (PD - FLC)

PD - FLC is a control system that combines the proportional-derivative (PD) control strategy with fuzzy logic. The development of the system shown in Figure 2 was necessary for the implementation of this particular part. In order to achieve this, the PD - controller was incorporated as an input to the fuzzy logic controller. Moreover, a set point was introduced to provide the capability of adjusting the water level in the tank to any desired value, which was not possible previously. Previously, the water level in the tank was solely determined by the balance between the input and output flow rate, resulting in a fixed level of five centimeters. However, with the introduction of the new system, as depicted in Figure 15, the water level in the tank can now be modified to suit any preferred value.

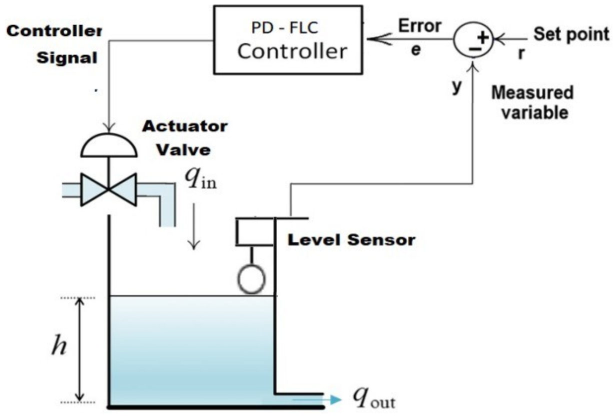


Figure 51: Schematic diagram of single tank level control system

The PD-FLC system utilizes two inputs to operate the fuzzy logic controller effectively. These inputs include the error signal e(t), which represents the difference between the desired set point and the measured value, and the change of the error signal Δe(t). The fuzzy logic controller output is the valve opening signal u(t). In figure 16, the arrangement exhibits a PD-FLC system that employs a fuzzy controller of the Mamdani type.

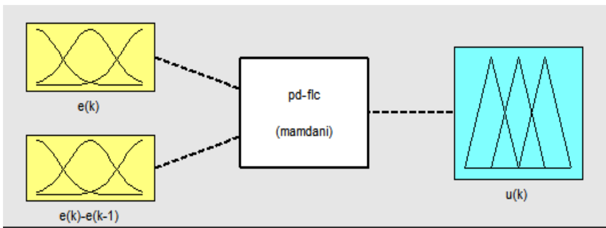


Figure 16: the PD-FLC system for Mamdani type

Figure 17 illustrates the membership functions of the fuzzy set for the first input "e(t), which are characterized as "Nigative Big (NB)," " Nigative Small (NS)," " Zero,(Z)" " Positive Small (PS)," and "" Positive Big (PB)," " within the range of **e(t)** ∈ **[-1 to 1].** On the other hand, Figure 18 illustrates the membership functions of the fuzzy set that characterize the second input " the change of error "Nigative Big (NB)," " Nigative Small (NS)," " Zero,(Z)" " Positive Small (PS)," and "" Positive Big (PB)," within the range of **Δe(t)∈ [-1 to 1].**

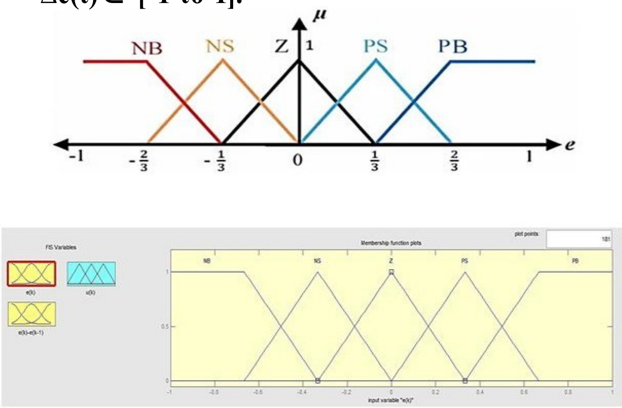


Figure 17: the First input "e(t)" of the PD-FLC system

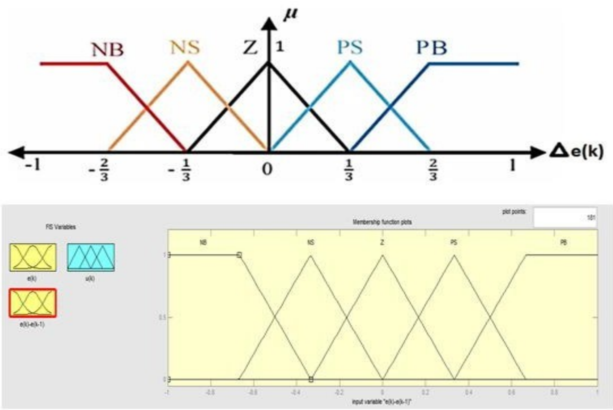


Figure 18: the second input "Δe(t)" of the PD-FLC system

4.3.1 Fuzzy Rules of The PD – FLC

After the fuzzification process is finished, the next step entails building a rule base that consists of the 25 subsequent rules. See table1

table1: PD – FLC Rules

PD – FLC Rules		e(k)				
		NB	NS	Z	PS	PB
Δe(k)	NB	NB	NB	NB	NS	Z
	NS	NB	NB	NS	Z	PS
	Z	NB	NS	Z	PS	PB
	PS	NS	Z	PS	PB	PB
	PB	Z	PS	PB	PB	PB

1. If (e(k) is NB) and (e(k)-e(k-1) is NB) then (u(k) is NB) (1)
2. If (e(k) is NB) and (e(k)-e(k-1) is NS) then (u(k) is NB) (1)
3. If (e(k) is NB) and (e(k)-e(k-1) is Z) then (u(k) is NB) (1)
4. If (e(k) is NB) and (e(k)-e(k-1) is PS) then (u(k) is NS) (1)
5. If (e(k) is NB) and (e(k)-e(k-1) is PB) then (u(k) is Z) (1)
6. If (e(k) is NS) and (e(k)-e(k-1) is NB) then (u(k) is NB) (1)
7. If (e(k) is NS) and (e(k)-e(k-1) is NS) then (u(k) is NB) (1)
8. If (e(k) is NS) and (e(k)-e(k-1) is Z) then (u(k) is NS) (1)
9. If (e(k) is NS) and (e(k)-e(k-1) is PS) then (u(k) is Z) (1)
10. If (e(k) is NS) and (e(k)-e(k-1) is PB) then (u(k) is PS) (1)
11. If (e(k) is Z) and (e(k)-e(k-1) is NB) then (u(k) is NB) (1)
12. If (e(k) is Z) and (e(k)-e(k-1) is NS) then (u(k) is NS) (1)
13. If (e(k) is Z) and (e(k)-e(k-1) is Z) then (u(k) is Z) (1)
14. If (e(k) is Z) and (e(k)-e(k-1) is PS) then (u(k) is PS) (1)
15. If (e(k) is Z) and (e(k)-e(k-1) is PB) then (u(k) is PB) (1)
16. If (e(k) is PS) and (e(k)-e(k-1) is NB) then (u(k) is NS) (1)
17. If (e(k) is PS) and (e(k)-e(k-1) is NS) then (u(k) is Z) (1)
18. If (e(k) is PS) and (e(k)-e(k-1) is Z) then (u(k) is PS) (1)
19. If (e(k) is PS) and (e(k)-e(k-1) is PS) then (u(k) is PB) (1)
20. If (e(k) is PS) and (e(k)-e(k-1) is PB) then (u(k) is PB) (1)
21. If (e(k) is PB) and (e(k)-e(k-1) is NB) then (u(k) is Z) (1)
22. If (e(k) is PB) and (e(k)-e(k-1) is NS) then (u(k) is PS) (1)
23. If (e(k) is PB) and (e(k)-e(k-1) is Z) then (u(k) is PB) (1)
24. If (e(k) is PB) and (e(k)-e(k-1) is PS) then (u(k) is PB) (1)
25. If (e(k) is PB) and (e(k)-e(k-1) is PB) then (u(k) is PB) (1)

4.3.2 Simulink Block Diagram of The PD – FLC

The controller output signal **u(k)** is an input to the valve actuator, which in turn determines the opening value. This opening value is proportional to the controller signal and gives an appropriate flow rate

$$u(k) = f(e(k), \Delta e(k)) \qquad (6)$$

The inputs are the error signal **'e(k)'** and the change of error signal '**Δe(k)**', and the outputs are the control output signal '**u(k)**'.

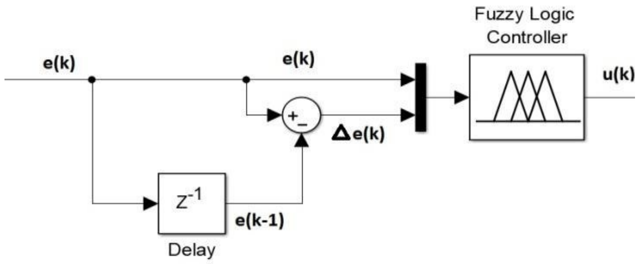


Figure 19: combines PD with FLC controller

Figure 20 represents the complete block diagram of the control system demonstrated in Figure 15. Within this block diagram, a feedback mechanism is incorporated using a sensor to measure the water level in the tank. The sensor converts the water level value into an electrical signal known as the measured value. Subsequently, the measured value is compared to the desired value (R), known as the set point, resulting in an error value. The error signal is then inputted to the fuzzy logic controller, which responds by determining the appropriate magnitude of the controller's output signal **u(k)**.

To standardize the water level measurement, it is necessary to multiply it by 100 in order to convert meters to centimeters. Additionally, the error signal is scaled by dividing it by the set point (R) to guarantee that the error values remain within the set point range. This scaled error signal is then employed as input to the fuzzy logic controller, which encompasses a member-function range from -1 to 1.

Finally, the output value of the fuzzy logic controller is multiplied by the set point (r), acting as a scaling factor. Subsequently, the error signal is transformed into a scaled representation ranging from zero to one, as opposed to the previous range of zero to 100. This converted ratio is then used as input for the valve, determining the corresponding valve opening ratio, ultimately resulting in an optimal water flow rate.

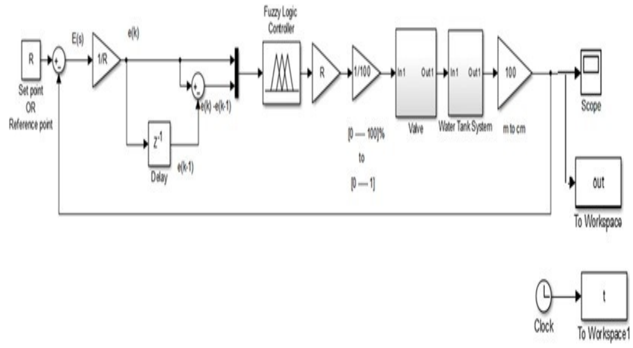


Figure 20: Simulink diagram of the PD-FLC system

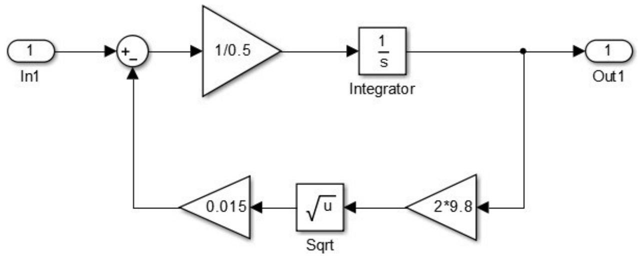


Figure 21: block diagram of the tank subsystem

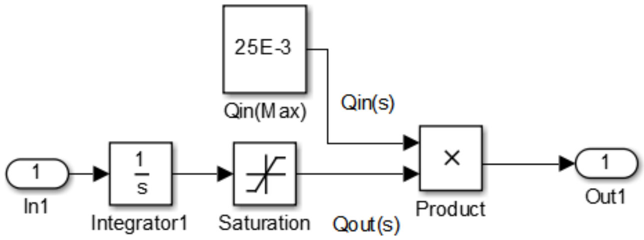


Figure 22: block diagram of the valve subsystem

5. Results and Discussion

The analyzing of the simulation outcomes for three different scenarios of water level control in the tank: single-input single-output fuzzy logic control (SISO FLC), multi-input single-output fuzzy logic control (MISO FLC), and proportional-derivative fuzzy logic control (PD-FLC). In the SISO FLC case, the fuzzy controller had one input and one output, as explained previously, and it had three rules linking the input of the single fuzzy controller with the output. After applying the simulation with the given data, the time response was shown in Figure 23.

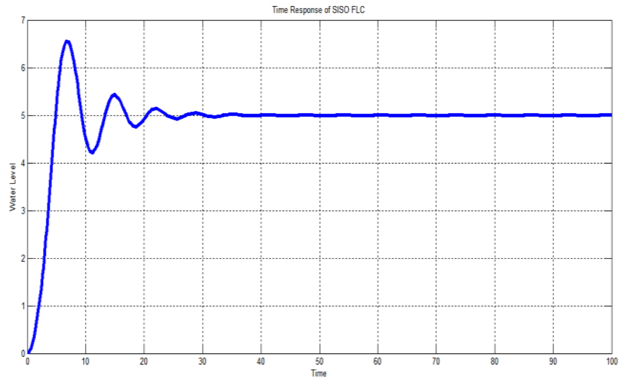


Figure 23: Response of SISO FLC

The stepinfo function in Matlab allows for the analysis of the step response properties of a system. By utilizing this function, different performance metrics such as rise time, settling time, and overshoot can be obtained. The parameters of the stepinfo function are calculated by adjusting the simout block to send the step response data of the system to Matlab.

```
stepinfo(out.Data,out.Time)
ans =

RiseTime: 5.1334
SettlingTime: 22.7284
Overshoot: 31.0673
```

In the MISO FLC case, the fuzzy controller had two inputs and one output, as explained previously, and it had five rules linking the input of the single fuzzy controller with the output. After applying the simulation with the given data, the time response was shown in Figure 24.

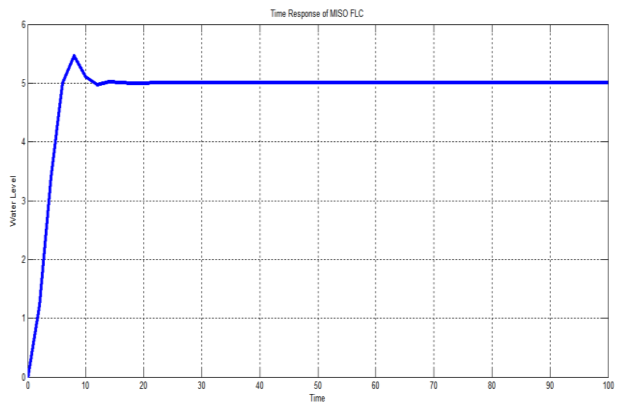


Figure 24: Response of MISO FLC

The characteristics of the step response for a MISO FLC system can be summarized as follows.
RiseTime: 4.5619
SettlingTime: 10.1682
Overshoot: 9.2553

In the case of the PD - FLC scenario, the fuzzy controller was equipped with two inputs and one output, as mentioned earlier. It comprised of a total of 25 rules that connected the input of the sole fuzzy controller with its output. Once the simulation was carried out using the provided data, the resulting time response was visualized in Figure 25.

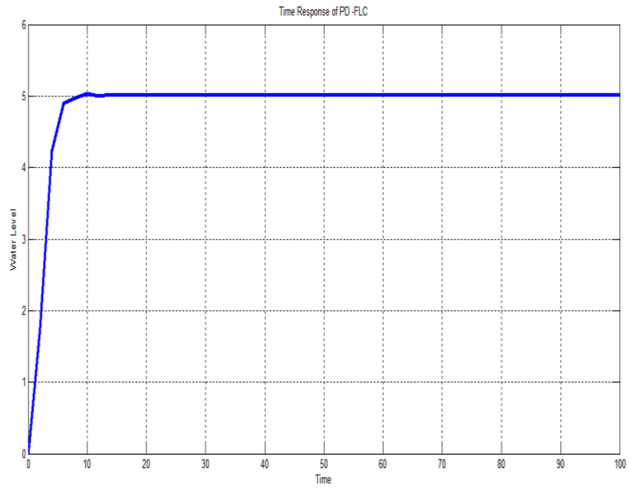


Figure 25: Response of PD-FLC system

The step response properties of a PD-FLC system are as follows.
RiseTime: 3.6894
SettlingTime: 4.712
Overshoot: 0.0004

Table2: Results

Parameter	SISO FLC	MISO FLC	PD - FLC
Overshoot	31.0673	9.2553	0.0004
Settling Time	22.7284	10.1682	4.712
Rise Time	5.1334	4.5619	3.6894

Table 2 shows the characteristics of the time response for the three cases. As we can see from the values, the best option is to use PD-FLC. In the case of PD-FLC, there is no overshoot, and the value is almost zero. Moreover, the system demonstrates high-speed performance in attaining the desired water level in the tank, and it quickly stabilizes at the desired level.

6. Conclusion

In the present study, three different techniques were investigated through the utilization of matlab/simulink to control the water level within the tank. These methods encompassed SISO FLC, MISO FLC, and PD-FLC. By comparing the outcomes obtained from these methodologies, it was evident that the pd-flc approach displayed superior performance in various aspects, including response time, speed of execution, and absence of overshooting. The SISO FLC technique involved using a single-input single-output fuzzy logic controller to control the water level in the tank. The MISO FLC technique utilized a multiple-input single-output fuzzy logic controller, taking into account multiple input variables to control the water level. Lastly, the PD-FLC technique combined the proportional-derivative control with fuzzy logic to control the water level. Through the utilization of Matlab/Simulink, the researchers were able to simulate and evaluate the effectiveness of these three techniques. The outcomes obtained from the simulations revealed that the PD-FLC approach outperformed the other two techniques in several aspects.

Firstly, the PD-FLC method displayed a superior response time. It was able to quickly respond to changes in the water level within the tank, ensuring fast adjustments to maintain the desired water level. This is crucial in situations where immediate and accurate control is necessary.

Secondly, the speed of execution of the PD-FLC technique was found to be excellent. It efficiently processed the input variables and provided effective control signals, resulting in a smooth and precise water level control. This is particularly important in real-time control systems where timely responses are required.

Lastly, one notable advantage of the PD-FLC approach was the absence of overshooting. Overshooting occurs when the control system overshoots the desired setpoint, leading to instability and inefficiency. The PD-FLC approach effectively prevented overshooting and maintained stable water level control.

Overall, the comparison of these three techniques highlighted the superiority of the PD-FLC approach in terms of response time, speed of execution, and absence of overshooting. The findings of this study provide valuable insights into the application of fuzzy logic and proportional-derivative control in controlling water levels, offering potential benefits in various industrial and engineering applications.

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