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Assessment of FLC, PID, Nonlinear PID, and SMC Controllers for Level Stabilization in Mechatronic Systems

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Abstract—**Liquid level measurement is a vital task in industries such as food processing, chemical manufacturing, and petroleum. The findings show that FLC and SMC offer superior performance in terms of rapid response, precision, and stability, particularly in handling nonlinear processes. By implementing these sophisticated controllers, industries put up benefit from increased work stability, low material waste, and improved energy efficiency. The study's results directly contribute to improving industrial applications by optimizing production and minimizing costs. The primary feather objective of a liquid level control system of rules is to exert a predetermined changeable level using a storage tank, measurement system, controller, and pump. This paper compares quaternary controllers: Fuzzy logical system Controller (FLC), Proportional-Integral-Derivative (PID), Nonlinear PID, and Sliding Mode verify (SMC) applied to some I and connected tankful systems. The FLC is an intelligent controller that excels at managing non-linear and uncertain systems by interpreting influx and outflow rates and adjusting the system to maintain desired unstable levels. Its adaptability to undefined scenarios is a key innovation. The PID controller is used as a benchmark undefined to its simplicity simply struggles with non-linear systems and time-varying parameters. The Non-linear PID controller improves upon the traditional PID by using wrongdoing saturation functions, providing better control in non-linear systems. The SMC is a robust control method that ensures system stableness in the front of disturbances and uncertainties, making it highly effective for heavy-duty applications. Simulation results show that FLC and SMC cater a faster response and better accuracy in reaching desired unstable levels compared to traditional PID controllers. Both systems demo robust stableness and efficient control. As seen in the provided data, the FLC reaches a steady-state level in as little as 8.34 seconds in Run 1 and 1.088 seconds in Run 2 for the single-tank system. Similarly, the SMC stabilizes the system in approximately 23.17 seconds in the coupled tank system, reflecting its robust control capabilities.**

Keywords*— *Intelligent Control; Liquid Level; Linear Control; Mechatronics; Nonlinear Control; Proportional-Integral-Derivative Control; Sliding Mode Control.

I. INTRODUCTION

The two crucial things that enable a mechatronic system to perform specific tasks with maximum control are accuracy and efficiency in design. Degraded process quality, inefficiency, and increased maintenance requirements are different problems that uncontrolled fluid levels can cause. Furthermore, when it comes to creating intelligent systems, mechatronics incorporates principles from computer, electrical, and mechanical engineering. Chemical, boiler, and nuclear power facilities need fluid-level management. An essential function. Fluid-level management must be precise to maximize process efficiency, minimize material waste, and maintain system stability. Clarity water levels, various applications, and benefits of control systems have been studied. First, they save power by reducing electricity and water use for regulation. Moreover, this system is useful in many industrial processes also reducing water and electricity waste, it saves money and energy [1]-[3].

Mechatronics systems modeling and control are essential for this application because they ensure precise and repeatable measurements. So, traditionally, PID controllers have been widely used for fluid level control in industrial settings. PID controllers calculate an error value based on the difference between the measured output and a desired set point. However, these controllers face challenges when dealing with non-linear processes characterized by inertial lag, time delay, and time-varying parameters. The task is difficult to effectively control nonlinear processes when adjusting the gains of Proportional-Integral-Derivative Control, (PID) controllers. Therefore, there is a need for alternative controller design methodologies that can overcome these limitations and provide robust and efficient control [4][5]. Patch PID controllers have been widely used for their simplicity and effectiveness in linear systems, they struggle with non-linear processes, time delays, and varying parameters. These limitations turn seeming when undefined with complex and uncertain systems, where the PID controller's performance can degrade. To address these challenges, alternative verify strategies such as FLCs are introduced. FLCs excel in handling non-linear and uncertain environments by using linguistic variables and illation rules to conform to dynamic changes, making them a more robust solution for managing complex processes.

Traditional control theory which relies on mathematical models of the process, Fuzzy logic relies on linguistic variables and IF-THEN rules [6]. Also, [7] suggested a model for controlling a liquid level in a tank utilizing FLC and IoT technologies.

Specific studies have been conducted on water level control systems as in [8], the operation and benefits of an automatic water level indicator and controller were discussed. Another paper focuses on PLC programming for a water level control system, highlighting its significance in industrial processes [9]. One research paper proposed to stabilize a nonlinear quadruple tank system and control the water levels of the lower two tanks in the presence of exogenous disturbances, parameter uncertainties, and parallel varying input set-points [10].

In [11], reviewed various developments in the optimization of irrigate applied mathematics statistical distribution systems using the technique of genetic algorithms. or s studies have been conducted on liquidness level based neural web control systems. One explores proposed a deep neuronic network approach to properly identify the irrigate level [12]. Another wallpaper focuses on the employ of Artificial corporeal cell network was designed for the level control of a round shape tank [13].

Moreover, SMC has found extensive use in a straddle of verify applications, much as liquid-level systems. Specifically, the management of two-tank liquid-level systems has garnered considerable matter to because of its importance in industrial processes and irrigate management applications. Wang et al. [14] studied the unrefined slippery mode control of nonlinear two-tank liquid-level systems. Furthermore, Zhang and Liu [15] explored the employment of fractional-order SMC in two-tank liquid-level systems. In addition, Li and Wu [16] projected an adaptive SMC strategy for two-tank liquid-level systems with uncertainties. An adaptive verify algorithm was planned by the authors, which is capable of estimating and compensating for uncertain system parameters.

In addition, Wang and Zhang [17] studied the implementation of event-triggered SMC on two-tank liquid-level systems. Xu and sunbathe [18] studied the practical application of ISMC to coupled-tank liquid-level systems with input constraints.

A liquid level systems play a crucial role in maintaining best levels of liquids in tanks, reservoirs, and other containers. They ensure efficient and condom operation by preventing run over or underflow, maintaining consistent levels, and enabling exact measurements.

The Proportional-Integral-Derivative (PID) controller has long been first harmonic in control systems due to its simplicity and effectiveness. Recent advancements include incorporating adjustive mechanisms or hybridizing PID with other techniques, such as FLCs, which excel in handling disturbances and uncertainties [19]-[31]. Recent research has focused on integrating AI with traditional verification methods to develop adaptive systems for complex heavy-duty processes [32]-[34]. The literature on fluid level stabilization in mechatronic systems highlights the ongoing evolution of control strategies. As heavy-duty processes become more complex, the demand for advanced control techniques that can provide robust and reliable public presentation will continue to turn [35]-[53].

These systems are vital for process control, tone assurance, and resource management. The integration of PID (Proportional-Integral-Derivative) and SMC in liquid systems has been a significant focus on of research from 2019 to 2024. These control strategies are crucial for maintaining desired liquid levels in various industrial applications, ensuring stableness and efficiency. The PID controller is notable for its simplicity and effectiveness in linear systems [54], while SMC offers robustness against system uncertainties and undefined disturbances [55]. Recent studies have focused on enhancing the performance of liquid-level systems by combining these two control strategies [56]. For instance, researchers have developed hybrid controllers that purchase the strengths of both PID and sliding mode control to reach better transeunt response and rock-bottom steady-state wrongdoing [57]. These hybrid systems are particularly effective in handling nonlinearities and time-varying dynamics commonly based on liquid-level processes [58].

In recent research, freshly approaches in the design of controllers have been implemented to mitigate chattering in SMC [59]. Furthermore, adaptive versions of PID controllers have been introduced to clarity performance under changing system parameters [60]. The use of robust control techniques has also been explored to further enhance disturbance rejection [61]. Advancements in sensor technology and real-time data processing have expedited the implementation of these verify strategies in more complex environments [62], [63]. This integration allows for more precise control actions [64].

Simulation studies have highlighted the adaptability of these hybrid controllers in versatile industrial scenarios [65], demonstrating that they can wield different configurations and operating conditions [66]. Moreover, simple machine learning techniques have been introduced to optimize controller parameters in real-time, thereby encourage enhancing system performance [67]. Researchers have besides explored the incorporation of semisynthetic intelligence techniques such as fuzzy logical system [68].

Other studies have focused on the application of these controllers in specific industrial sectors. For example, in chemical substance process industries [69]. The water handling industry has as well benefited from these advanced verify strategies, achieving better performance in maintaining liquid levels across different storage tanks [70].

In addition, the purpose of fault detection and recovery in PID-SMC systems has been researched, aiming to minimize downtime in critical processes [71]. Researchers have continued to refine these techniques to handle a broader straddle of disturbances [72]. Future research is expected to search the deployment of these techniques in autonomous systems and more advanced industrial processes [73].

Our main objective of the present work is to design, simulate, and compare the performance of foursome distinct control strategies—FLC, classical PID control, nonlinear PID control, and SMC—for liquid level stabilization in both single and coupled tankful mechatronic systems. The study aims to tax these controllers in terms of response time, stability, precision, and hardiness to disturbances, ultimately identifying the most effective verify method for maintaining desired fluid levels in heavy-duty applications.

The motivation for this contemplates arises from the limitations of traditional PID controllers in handling nonlinear liquid-level systems, which often lead to inefficiencies and instabilities in heavy-duty applications. Advanced control techniques like FLC and SMC improved performance, especially in nonlinear and time-varying environments. The study aims to liken these controllers to place the most effective method for achieving precise and stable fluid level control. By optimizing control strategies, this research seeks to raise industrial process efficiency and reduce vitality waste. The findings will contribute to development more robust and adaptive verify systems for critical industrial operations.

Research Gap: The introduction clearly outlines the limitations of PID controllers in treatment nonlinear processes, particularly in time-varying and delayed-response systems. It highlights the challenges two-faced by PID controllers in maintaining fluid levels in mechatronic systems under these conditions, which necessitates the exploration of alternative controllers as FLC and SMC.

The primary goal of this research is to design, simulate, and compare four verify strategies— FLC, linear PID control, nonlinear PID control, and SMC specifically for liquid level stabilization in one and two-tank systems. The evaluation focuses on describing performance metrics such as response time, stability, precision, and robustness to disturbances. The last aim is to identify the to the highest degree effective control scheme for maintaining fluid levels in industrial applications.

This paper presents both a prior analysis and simulation results to validate the effectiveness of these control methods. The research focuses on designing SMC, FLC, and classical linear and nonlinear verify strategies for fluid applications. Each proposed restrainer aims to maintain the wanted fluid level in the tankful by adjusting the output valve. The FLC, designed using MATLAB, uses inputs such as inflow and outflow rates and applies a set of rules to determine the appropriate verify action. The FLC controller operates based on five rules for each input, with 1 output parameter using five membership functions.

Contributions: The paper contributes to the field by:

Offering a comprehensive undefined of four different control strategies (FLC, PID, nonlinear PID, and SMC) for unstable level stabilization.

Demonstrating the master performance of FLC and SMC in handling nonlinearities and disturbances in liquidness level control systems, compared to traditional PID controllers.

Providing a detailed public presentation analysis through simulation results, which highlights the faster response times and cleared accuracy of FLC and SMC controllers in industrial applications.

Introducing new control design insights and validating these approaches with MATLAB-based simulations, particularly for single and coupled tankful systems.

Thus, the introduction provides a clear context for the research, effectively stating the gap, goals, and contributions that address the specific challenges in controlling fluid levels in nonlinear and mechatronic systems.

The remaining sections of this work are laid out as follows: mathematical model in section two, In section three components controllers' design. Results and discussion in section four and conclusions in section five. Finally, section six clarifies future work suggestions.

The research methodology adopted in this contemplate follows an organized work to check comprehensive examination data collection, analysis, and interpretation. The steps below typify the research's key phases, from problem recognition to final evaluation. A flowchart is presented to ply a clear visual summary of the methodology employed in this study (Fig. 1).

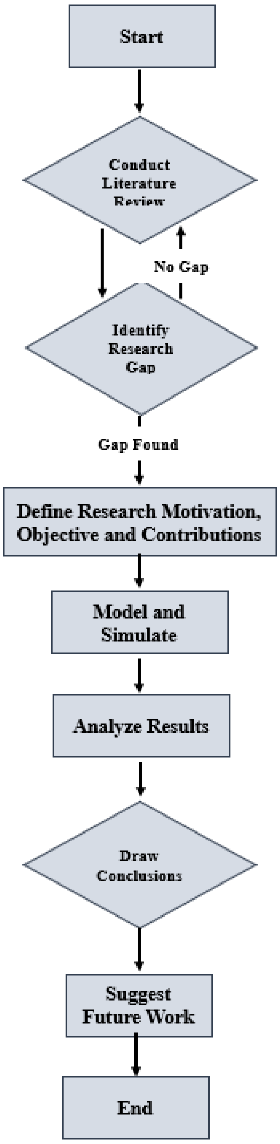


Fig. 1. Overview of the Research Methodology

II. MATHEMATICAL MODELING

The modeling and control of mechatronics systems for this application are crucial to ensure correct and reliable measurements. Mathematical process models are required for various steps in the design of mechatronic systems, such as simulation and control. The design of mechatronic systems can be divided into some stages, including the need identification, market research, and applied science selection.

The control of mechatronic systems involves the integration of electronics and computer science technologies with the mechanical system throughout the design process [1]-[3].

In much systems, fluid from the pump is allowed to enter the tank when the verify signal is generated by the controller. Suppose, the controller actuates the pump and the pump starts filling the tankful with an inflow rate of $Q_i\ {}^{m^3}/_{s}$. Here h denotes the fluid level inside the tank in m and it is constant. Q_o be the natural spring rate of the fluid from the tank. It is clear that to wield a steady take down of the liquid, $Q_i = Q_o$.

A. Single Tank System

Resistance and capacitance are the two important terminologies in two- tank systems. Resistance of the liquidity rase is defined as transfer in the tear down remainder 'tween the two tanks which needfully causes a whole change in flow rate. So, generally, the resistance of the liquid state level system is as:

$$R = \frac{Variation\ in\ level\ difference\ (m)}{Change\ in\ rate\ of\ flow\ \left({}^{m^3}/_{s}\right)} \tag{1}$$

Capacitance of the liquid level is defined as change in quantity of stored liquid to cause a unit charge in the potential head. The energy level of the system indicates the potential of the liquid level system.

$$C = \frac{Change\ in\ liquid\ stored\ (m^3)}{Change\ in\ head\ (m)} \tag{2}$$

This is explained on the basis of the marked change between the level of the two tanks necessary for a change in one of the flow rates This means that the ratio depends on the flow rate. Assume that the flow is linearly turbulent where:

- Q_o denotes the steady-state outflow rate
- q_i represents a small change in the rate of inflow from the steady state value
- q_o indicates a small change in the rate at which the flow leaves steady state
- H is the steady state of water in the tank
- h is the smallest change in water level from the steady state value

Table I clarifies the dimension of the tank [74]. Fig. 2 represents the liquid level system

TABLE I. THE DIMENSION OF THE TANK (IN GENERAL) [74]

Properties	Values
The height of the tank, h(m)	1
The diameter of the tank, d(m)	0.15
The cross-sectional area of the tank, A(m^2)	0.5063
The capacitance of the tank, C $\left({}^{m^3}/_{m}\right)$	0.5063
The volume of the tank, V(m^3)	0.0176
The maximum liquid flow, $Q_o\left({}^{1}/_{s}\right)$	0.5
The maximum liquid flow, $Q_o\left({}^{m^3}/_{s}\right)$	0.0005
Resistance, R $\left({}^{s}/_{m^2}\right)$	2000

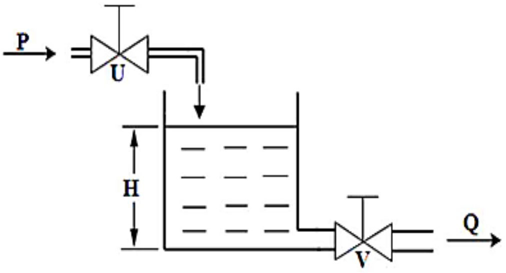


Fig. 2. Schematic diagram of liquid level system for single-capacity tank [75]

The equation of capacitance for liquid level system is given by:

$$C\frac{dh}{dt} = q_i - q_o \tag{3}$$

$$C\ dh = (q_i - q_o)dt \tag{4}$$

as:

$$R = \frac{h}{q_o} \tag{5}$$

$$q_o = \frac{h}{R} \tag{6}$$

Also, on substituting the value of q_o, yield,

$$C\ dh = \left(q_i - \frac{h}{R}\right)dt \tag{7}$$

$$RC\ dh = (Rq_i - h)dt \tag{8}$$

Further,

$$RC\frac{dh}{dt} = Rq_i - h \tag{9}$$

On transforming

$$RC\frac{dh}{dt} + h = Rq_i \tag{10}$$

Accordingly, the time domain of the single tank system is given by;

$$\dot{x} = -ax + bu \tag{11}$$

where $x = h, u = q_i$, $a = \frac{1}{RC}$ and $b = \frac{1}{C}$.
The value of each one of these nominal parameters in Table II.

TABLE II. SINGLE TANK SYSTEM NOMINAL PARAMETERS

Parameter	Description	Formula/ Equation	Value and Unit
x	State variable (height)	$x = h$	run 1= 0.8 m run 2= 1 m
u	Input variable	$u = q_i$	$0.0005\left({}^{m^3}/_{s}\right)$
a	Constant (resistance and capacitance)	$a = \frac{1}{RC}$	$\frac{1}{RC} = \frac{1}{2000 \times 0.5063}$ $= 0.00098755678\ s$
b	Constant (capacitance)	$b = \frac{1}{C}$	$\frac{1}{C} = \frac{1}{0.5063}$ $= 1.975113569030219\ \frac{1}{\left({}^{m^3}/_{m}\right)}$

To use the mathematical model in designing the Fuzzy logic controller, we need to derive the transfer function of the single tank system as follows; taking Laplace transform, yield:

$$RC\, sH(s) + H(s) = RQ_i(s) \tag{12}$$

$$H(s)(sRC + 1) = RQ_i(s) \tag{13}$$

Thus, the transfer function of the system for input q_i and output h, we will have,

$$\frac{H(s)}{Q_i(s)} = \frac{R}{1 + s\,RC} \tag{14}$$

While if q_o is considered as the output for input qi, then the Laplace transform of the equation shown above i.e.,

$$q_o = \frac{h}{R} \tag{15}$$

Will be

$$Q_o(s) = \frac{H(s)}{R} \tag{16}$$

So, on substituting, $H(s)$ from the transfer function obtained

$$Q_o(s) = \frac{Q_i(s)}{1 + s\,RC} \tag{17}$$

above, we will get,

$$\frac{Q_o(s)}{Q_i(s)} = \frac{1}{1 + s\,RC} \tag{18}$$

Therefore, RC corresponds the time constant i.e., T, of the liquid level control system.

B. Coupled Tank System

Consider the system two tanks interact. Thus, the transfer function of the system is not the product of two first-order transfer functions. In the following, we shall assume only small variations of the variables from the steady-state values. So, the following equations for this system in Fig. 3.

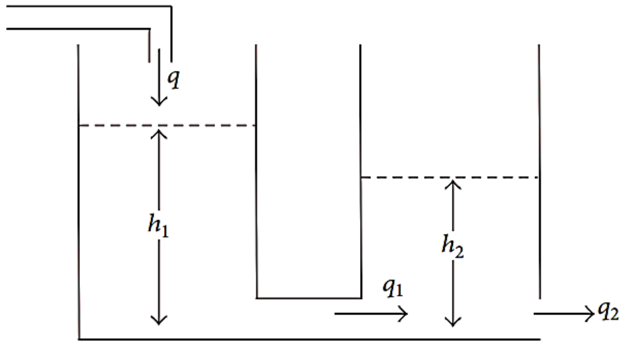


Fig. 3. A schematic diagram of the coupled tanks system

For Tank 1

$$C_1 \frac{dh_1}{dt} = (q - q_1) \tag{19}$$

$$q_1 = \frac{h_1 - h_2}{R_1} \tag{20}$$

$$C_1 \frac{dh_1}{dt} = \left(q - \frac{h_1 - h_2}{R_1}\right) \tag{21}$$

$$C_1 R_1 \frac{dh_1}{dt} = R_1 q - h_1 + h_2 \tag{22}$$

$$T_1 = C_1 R_1 \tag{23}$$

Taking Laplace transform for both side:

$$T_1 s h_1(s) + h_1(s) - h_2(s) = R_1 q(s) \tag{24}$$

$$h_1(s)(T_1 s + 1) - h_2(s) = R_1 q(s) \tag{25}$$

$$h_1(s) = \frac{R_1 q(s)}{(T_1 s + 1)} + h_2(s) \tag{26}$$

For Tank 2

$$C_2 \frac{dh_2}{dt} = (q_1 - q_2) \tag{27}$$

Assume linear resistance to flow

$$q_2 = \frac{h_2}{R_2} \tag{28}$$

$$C_2 \frac{dh_2}{dt} = \left(\frac{h_1 - h_2}{R_1} - \frac{h_2}{R_2}\right) \tag{29}$$

$$R_1 R_2 C_2 \frac{dh_2}{dt} = (h_1 - h_2)R_2 - h_2 R_1 \tag{30}$$

$$T_2 = C_2 R_2 \text{ or } A_2$$

$$T_2 R_1 \frac{dh_2}{dt} + h_2 R_2 + h_2 R_1 = h_1 R_2 \tag{31}$$

Taking Laplace transform on both sides

$$T_2 R_1 s h_2(s) + h_2(s) R_2 + h_2(s) R_1 = h_1(s) R_2 \tag{32}$$

$$(T_2 R_1 s + R_2 + R_1) h_2(s) = h_1(s) R_2 \tag{33}$$

substitute (26) in eq. (33) yield:

$$(T_2 R_1 s + R_2 + R_1) h_2(s) = \left(\frac{R_1 q(s)}{T_1 s + 1} + h_2(s)\right) R_2 \tag{34}$$

$$(T_2 R_1 s + R_2 + R_1) h_2(s) = \frac{R_1 R_2 q(s)}{T_1 s + 1} + R_2 h_2(s) \tag{35}$$

Solving above equation

$$\begin{aligned} R_1(T_1 s + 1)(T_2 s + 1) h_2(s) \\ + +R_2 h_2(s)(T_1 s + 1) \\ - R_2 h_2(s) = R_1 R_2 q(s) \end{aligned} \tag{36}$$

$$\begin{aligned} R_1 h_2(s)(T_1 T_2 s^2 + T_1 s + T_2 s + 1) + R_2 h_2(s) T_1 s \\ + R_2 h_2(s) - R_2 h_2(s) \\ = R_1 R_2 q(s) \end{aligned} \tag{37}$$

$$\begin{aligned} h_2(s)[R_1(T_1 T_2 s^2 + (T_1 + T_2)s + 1) + R_2 T_1 s] \\ = R_1 R_2 q(s) \end{aligned} \tag{38}$$

$$\frac{h_2(s)}{q(s)} = \frac{R_1 R_2}{[R_1(T_1 T_2 s^2 + (T_1 + T_2)s + 1)] + R_2 T_1 s} \tag{39}$$

Substitute eq. (23) in eq. (39) yield:

$$\frac{h_2(s)}{q(s)} = \frac{R_1 R_2}{[R_1(T_1 T_2 s^2 + (T_1 + T_2)s + 1)] + R_2 C_1 R_1 s} \tag{40}$$

$$\frac{h_2(s)}{q(s)} = \frac{R_1R_2}{R_1[T_1T_2s^2 + (T_1 + T_2 + C_1R_2)s + 1]} \tag{41}$$

$$\frac{h_2(s)}{q(s)} = \frac{R_2}{(T_1T_2s^2 + (T_1 + T_2 + C_1R_2)s + 1)} \tag{42}$$

As for the single tank system, the time domain model for the coupled tank system (Eqs. (22) and (30)) which represented by the state space form is given by

$$\frac{dx_1}{dt} = -a_1x_1 + a_2x_2 \tag{43}$$

$$\frac{dx_2}{dt} = b_1x_1 - b_2x_2 + \mathrm{c}u \tag{44}$$

where, $x_1 = h_2,\ x_2 = h_1, u = q$, $a_1 = (R_1 + R_2)/R_1R_2C_2$, $a_2 = 1/R_1C_2$, $b_1 = b_2 = 1/R_1C_1$, and $\mathrm{c} = 1/C_1$.

The value of each one of these nominal parameters in Table III.

TABLE III. COUPLED SYSTEM PARAMETERS

Parameter	Description	Formula/ Equation	Value and Unit
x_1	State variable 1 (height 2)	$x_1 = h_2$	run 1= 0.8 m run 2= 1 m
x_2	State variable 2 (height 1)	$x_2 = h_1$	-
u	Input variable	$u = q$	$0.0005\left(m^3/s\right)$
a_1	Constant (resistance and capacitance)	$a_1 = \frac{R_1 + R_2}{R_1 + R_2C_2}$	$a_1 = \frac{4.379\ + 2.939}{4.379 + (2.939 \times 0.506} = 1.24731215565 \frac{1}{\left(m^3/m\right)}$
a_2	Constant (resistance and capacitance)	$a_2 = \frac{1}{R_1C_2}$	$a_2 = \frac{1}{4.379 \times 0.5063} = 0.45104214867\ s$
b_1	Constant (resistance and capacitance)	$b_1b_2 = \frac{1}{R_1C_1}$	$b_1b_2 = \frac{1}{4.379 \times 0.5063} = 0.45104214867\ s$
c	Constant (capacitance)	$b = \frac{1}{C_1}$	$b = \frac{1}{C_1} = \frac{1}{0.5063}\ \frac{1}{\left(m^3/m\right)}$

III. CONTROLLERS DESIGN

Three The crucial components of the liquid level control system are fluid tank also known as a storage tank, used to hold the desired amount of fluid. Measurement system senses the level of the fluid inside the tank. Controller used to maintain the desired level by starting and stopping the pump when gets information by the measurement system. Pump: The water from the source is fed to the tank through the pump when actuated by the controller. Fig. 4 represents the liquid level system.

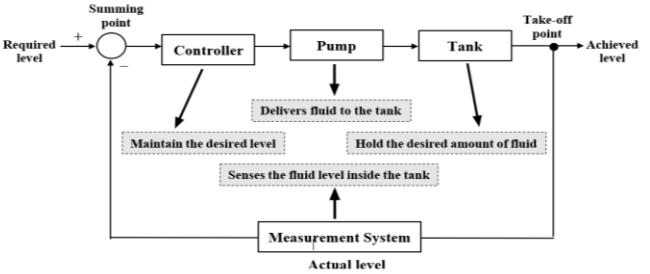


Fig. 4. Liquid level control system block diagram

This Fig. 4 displays a block diagram of a liquid-level control system, typically used in mechatronics engineering. The following is a concise explanation: Sensor Input detects the current liquid level and sends this data to the controller. While controller action analyzes input data against desired levels and computes the required adjustments. In addition, the actuator output executes the necessary actions to adjust the liquid flow, maintaining the desired level.

However, advantages of liquid level systems in mechatronics engineering: firstly, precision and control ensure accurate fluid level maintenance within tanks and systems, crucial for many industrial processes. Secondly, automation reduces the need for manual monitoring and adjustment, increasing efficiency and safety. Finally, versatility can be applied in various contexts from simple water tanks to complex chemical processing plants [76], [77] and [78].

Liquid level control systems find significant applications in numerous industries, including chemical processing plants for controlling the levels of chemicals in tanks to ensure proper mixing and avoid spills. Also, water treatment facilities for maintaining water levels in reservoirs and tanks for supply management and flood prevention. In addition to food and beverage industry for regulating liquid levels in production processes, such as brewing or bottling. Moreover, Oil and gas industry for monitoring and controlling liquid levels in storage tanks and pipelines [10]. Liquid level control systems are essential in mechatronics engineering and have a wide range of applications.

A. FLC

It is requisite for mechatronics engineer work in industries that trust on precise liquid level management to have a solid-state understanding of the design and surgical operation of liquid level verify systems. In liquid level control systems, it is possible to apply variety of control algorithms. One of these algorithms, identified as FLC. FLC provides robustness, ensuring stability in variable environments [79]. They offer superior performance and precise liquid level control compared to traditional methods like PID controllers [80]. Additionally, FLCs are easier to implement, reducing development costs and complexity [81].

FLC makes use of linguistic variables in rules in order to make decisions based on input that is imprecise or ambiguous. It offers a framework that is both versatile and durable for the design of control systems [10]. Fig. 5 shows block diagram of FLC [82].

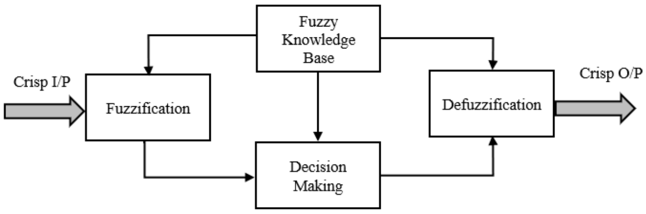


Fig. 5. Block diagram of FLC [82]

FLC structure consists of four main components: Fuzzification unit converts real scalar input values into fuzzy values using linguistic terms and membership functions. Fuzzy knowledge base stores the rules and membership functions defining the fuzzy relationships.

Decision making unit applies the fuzzy rules to the fuzzified inputs to infer the control actions. Defuzzification unit converts the fuzzy output values back into crisp values for the control action.

In summary, fuzzification transforms crisp inputs into fuzzy values, enabling the application of fuzzy logic for control decisions. Advantages of FLC include lower cost, robustness, customizability, human-like deductive reasoning, reliability, and efficiency [82].

B. PID

Additionally, the PID control strategy is a popular method that makes adjustment to the output of the actuator based on the difference between levels that are to be measured and those that are intended. The following is a list of the general output equations provided by the PID controller in both the time domain and the Laplace domain:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de}{dt} \tag{45}$$

$$u(t) = K_p \left[e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{de}{dt} \right] \tag{46}$$

$$G(s) = K_p + \frac{K_i}{s} + K_d s = \frac{K_d s^2 + K_p s + K_i}{s} \tag{47}$$

Where, $u(t)$ is the controller output signal fed to the process to be controlled, $e(t)$is the error signal: The difference between the set point and the measured process variable $e(t) = r(t) - b(t)$. K_p, K_i and K_d are the controller gain parameters equal respectively 120, 30 and 10, T_i is the integral time constant and T_d is the derivative time constant. The gain parameters K_i and K_d in Laplace domain equation are calculated by the equations $K_i = {Kp}/{T_i}$ and $K_p \cdot T_d$, respectively. PID control accumulates itself all characteristic features of P control, I control and D control and thus, sometimes called three-term control.

The nonlinear PID control law is proposed by replacing the integral of the error function with the integral of the error saturation function, by adjusting the parameters of the saturation function.

$$u_{NPID} = k_p e + k_i \int_0^t sat_\gamma e \, dt + k_d \dot{e} \tag{48}$$

Where, Sat_γ: the saturation function given by:

$$Sat_\gamma(e) = \gamma * sign(e) \tag{49}$$

Moreover, let, the design parameter γ for the nonlinear PID controller, $\gamma = 2$.

C. SMC design for Single Tank System

The first step in designing a SMC is the selection of the sliding variable s_o. The sliding variable for the single tank system (50) is defined as;

$$s_o = x - x_d \tag{50}$$

where $x_d = h_d$. In the present work, a modified time dependent sliding variable $s(t, s_o)$ is proposed as follows;

$$s(t, s_o) = s_o - e^{-\left(\frac{t}{\alpha}\right)} s_o(0) \tag{51}$$

where α is a positive constant which selected according to the system dynamic characteristics.

Remark 1: from the proposed sliding variable above one can show that $s(0, s_o) = 0$, also for $t \gg \alpha$, $s(t, s_o) = s_o$.

Remark 2: as in classical selection of sliding variable, the sliding manifold is defined by $s_o = e^{-(t/\alpha)} s_o(0)$ and for $t \gg \alpha$, $s_o \to 0$. Accordingly, $x \to x_d$ as $t \to \infty$.

Since the initial value of the sliding variable is equal to zero ($s(0, s_o) = 0$), then the Barrier function can be used to adaptively determine the SMC gain. The proposed SMC in the present work is given by;

$$u = k \frac{|s|}{\epsilon - |s|} \tag{52}$$

where ϵ is a small constant which determine the boundary layer thickness and consequently the steady state error, and $k > 1$ is a design parameter used selected according to the desired steady state error.

Remark 3: Since the control input is positive physically, then the control u is subjected to the following condition;

$$u = Q . k \frac{|s|}{\epsilon - |s|} \tag{53}$$

where $Q = \begin{cases} 1 \; if \; s \leq 0 \\ 0 \; if \; s > 0 \end{cases}$.

Remark 4: as $t \to \infty$. The steady state error is given by

$$|x - x_d| \leq (\epsilon / k) \tag{54}$$

D. SMC design for Coupled Tanks System

As for the single tank system, we need first to assign a classical sliding variable s_o. For the coupled tanks system, it can be takin as

$$s_o = \frac{dx_1}{dt} + c x_1 \tag{55}$$

where we assume that $\frac{dx_1}{dt}$ can be measured or estimated accurately. Consequently, as in Eq. (51), the time varying sliding variable s is given by

$$s(t, s_o) = s_o - e^{-\left(\frac{t}{\alpha}\right)} s_o(0) \tag{56}$$

and the control u is given by

$$u = Q * k \frac{|s|}{\epsilon - |s|} \tag{57}$$

where Q, k and ϵ are as defined in for the single tank system.

IV. RESULTS AND DISCUSSION

The results and discussion section comprehensively evaluates the performance of the different control strategies, offering a detailed comparison based on key performance metrics such as stability, adaptability, and response time. The analysis highlights how each controller—FLC, PID Linear, PID Non-Linear, and Sliding Mode Controller (SMC)—addresses specific challenges in controlling complex systems. It underscores the superior adaptability of the FLC, the reliability of PID controllers in linear systems, and the robustness of the SMC in handling uncertainties. The discussion integrates these findings to provide a nuanced understanding of the trade-offs involved in selecting an appropriate control strategy for varying system demands. This section ultimately emphasizes the critical role of choosing the right controller to achieve optimal system performance under diverse operational conditions.

A. Results of 1st, 2nd and 3rd Controllers i.e., FLC, PID L and PID NL

For single tank liquid level control system and based on the results from Fig. 6 to Fig. 13, you've got provided from the fuzzy common sense-based totally system for a single tank liquid level system. These Figures suggest that a Mamdani-type fuzzy inference device turned into applied, with two inputs—error and change of error—and one output, that's control. The department of the input space into linguistic variables (NM, NS, Z, PS, PM) shows a properly-based approach to the error and its change of error, which might be crucial on top of things systems for retaining stability and reaching preferred reaction characteristics. Performance of the system setup of 25 rules in the FLC in all likelihood presents a robust framework for managing numerous scenarios within the control of the tank's liquid level. It would be useful to review the real overall performance records or experimental outcomes to evaluate how successfully those guidelines translate into keeping the desired liquid stage, in particular underneath various input conditions. Moreover, sensitivity analysis analyzing how sensitive the system's output is to versions in enter can assist in excellent-tuning the fuzzy units or the regulations. Sensitiveness analysis is crucial to understanding how variations in input parameters (like inflow value and tank dimensions) influence the system's output, and can assist in fine-tuning the FLC's fuzzy sets or rules. It helps in ensuring stability, precision, and responsiveness under ever-changing conditions. This may lead to upgrades in precision and responsiveness.

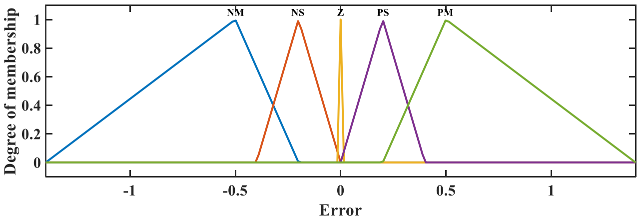


Fig. 6. Error Membership Function

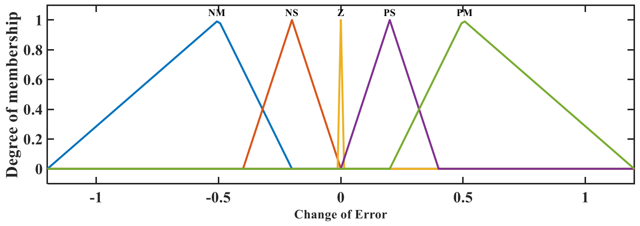


Fig. 7. Change of Error Membership Function

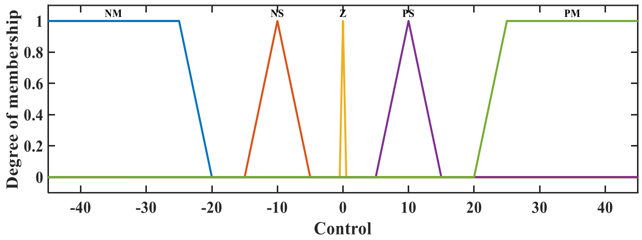


Fig. 8. Control Membership Function

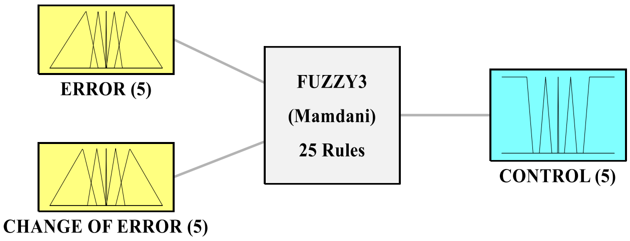


Fig. 9. Fuzzy Logic Control System Diagram

The number of rules equal 25 of FLC for single tank liquid level system. Here some of them.

If the error is Negative Medium (NM) and the change of error is Zero (Z), then the control action is Negative Medium (NM).

If the error is Positive Small (PS) and the change of error is Negative Small (NS), then the control action is Positive small (PS).

If the error is Zero (Z) and the change of error is Positive Medium (PM), then the control action is Positive Medium (PM).

If the error is Positive Medium (PM) and the change of error is Negative Medium (NM), then the control action is Negative Medium (NM).

If the error is Negative Small (NS) and the change of error is Positive Small (PS), then the control action is Negative Small (NS).

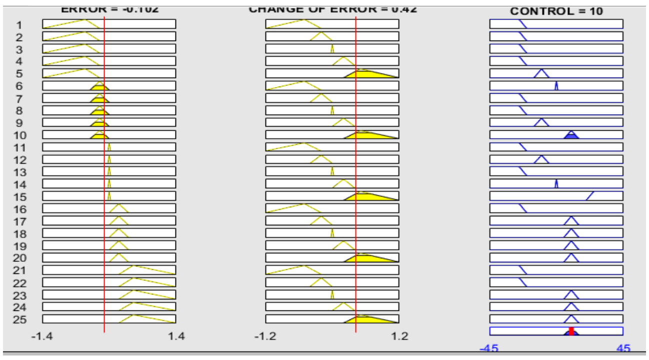


Fig. 10. Fuzzy Inference System Block Diagram

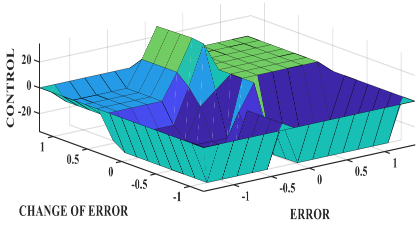
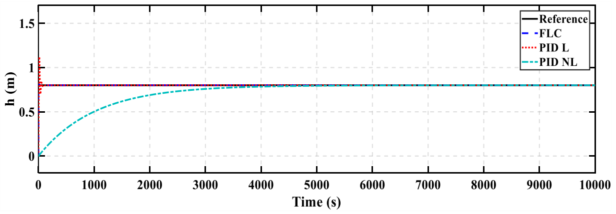
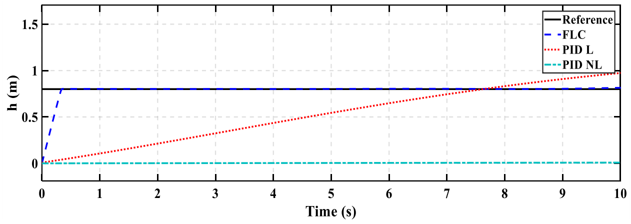


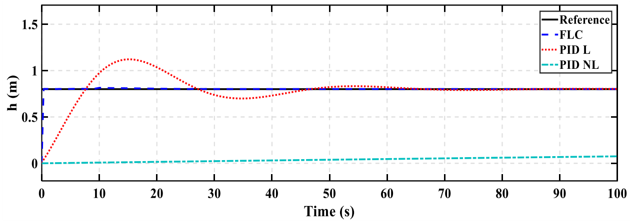
Fig. 11. Control Surface of the Fuzzy Logic Controller



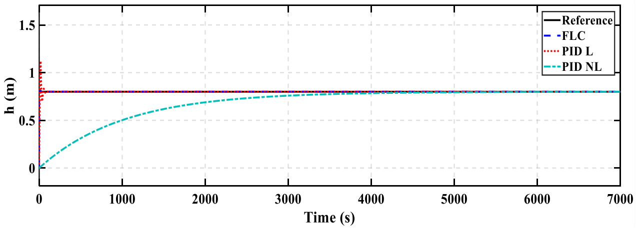
(a) Closed view of region between (0-10000) seconds



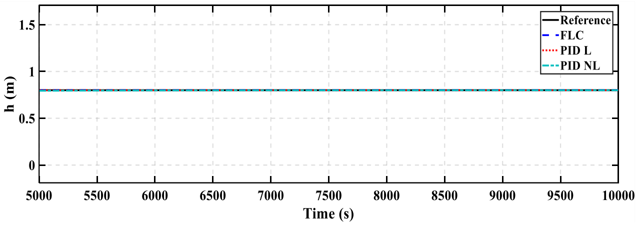
(b) Closed view of region between (0-10) seconds



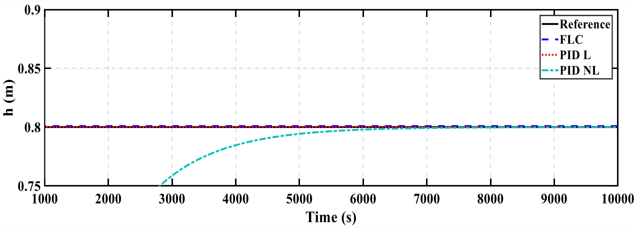
(c) Closed view of region between (0-100) seconds



(d) Closed view of region between (0-7000) seconds

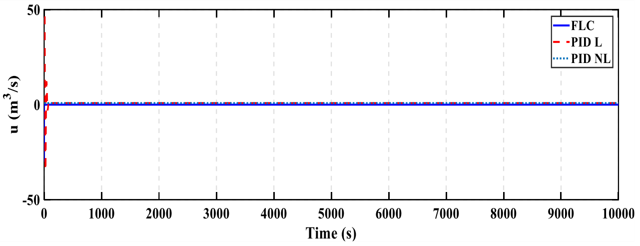


(e) Closed view of region between (5000-10000) seconds

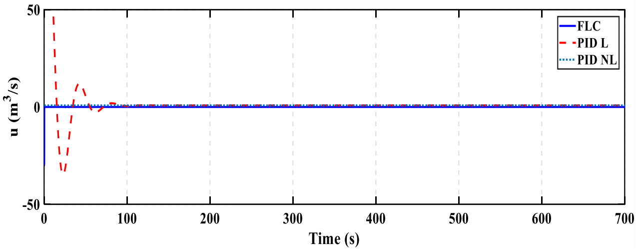


(f) Closed view of region between (1000-10000) seconds

Fig. 12. Run 1 analysis of single tank liquid level system (Desired Point = 0.8 m)



(a) Closed view of region between (0-10000) seconds



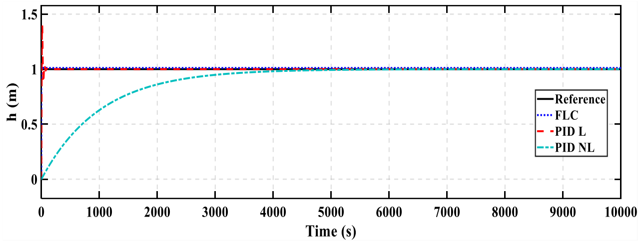
(b) Closed view of region between (0-700) seconds

Fig. 13. Control action of single Tank in run 1

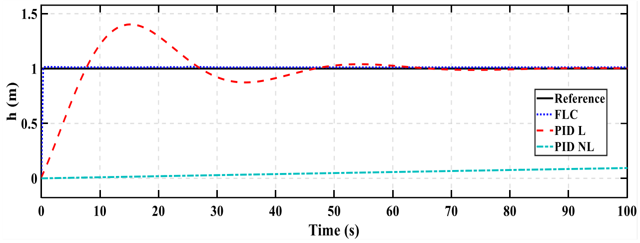
In scenario 1 or run 1, the system has reached the steady state at minimum time and the steady state error has been obtained as 0% for both intelligent and linear controller. While nonlinear controller reached the steady state too late time in addition to the steady state error has been obtained as approximately 0%, Table IV clarify that. Analyzing the results from the single tank system controlled by FLC, it is evident that the system performs distinctively when comparing the height of the tank h and the control signal u with other control methods like PID both L and NL: Now in another desired point as run2 of single tank liquid level system, Fig. 14 and Fig. 15 clarified each of height h (m) and control action u.

TABLE IV. THE SUMMARIZED ANALYSIS OF SINGLE TANK LIQUID LEVEL SYSTEM RUN1 AND RUN 2

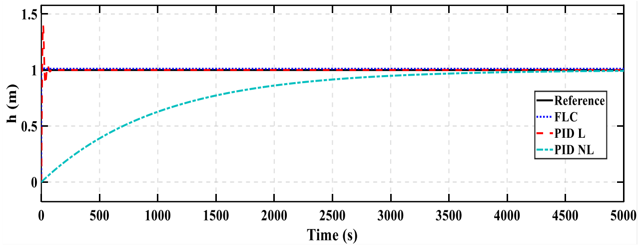
Aspect	**Run 1 FLC Performance**	**Run 2 FLC Performance**
Control Signal Responsiveness	Provides nuanced response with frequent, smaller adjustments	Efficiently adjusts tank height with dynamic control signal
Precision	Ensures precise control over fluid level, minimizing fluctuations	Maintains desired height with high precision
Stability and Settling Time	Quicker settling time, reaching desired height faster	Quick stabilization, crucial for productivity and safety
System Response Time	Enhances system efficiency by reducing response time	Robust control strategy, handles system perturbations quickly
Overshoot and Stability	Less overshoot, suitable for delicate systems	Avoids excessive oscillations, maintains smooth operation
System Stability and Performance	Demonstrates superior stability with minimal overshoot	Maintains system stability with minimal deviation from setpoint
Suitability for Applications	Ideal for applications requiring fine-tuned control and minimal overshoot	Better suited for industrial applications needing precision and stability
Comparison with PID Controllers	Outperforms PID controllers in precision, responsiveness, and stability	Outperforms PID controllers in adjusting control signals and maintaining desired height



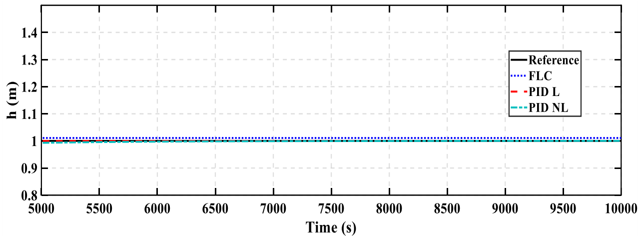
(a) Closed view of region between (0-10000) seconds



(b) Closed view of region between (0-100) seconds

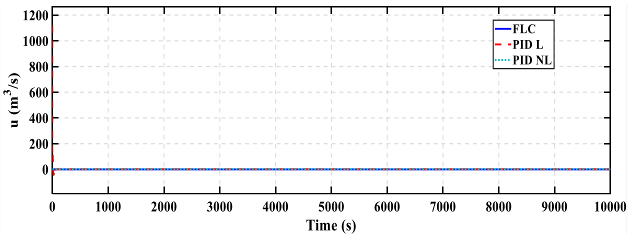


(c) Closed view of region between (0-5000) seconds

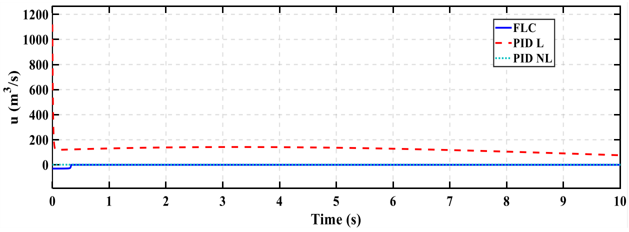


(d) Closed view of region between (5000-10000) seconds

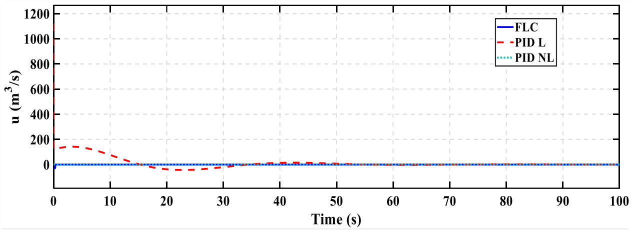
Fig. 14. Run 2 analysis of single tank liquid level system (Desired Point = 1 m)



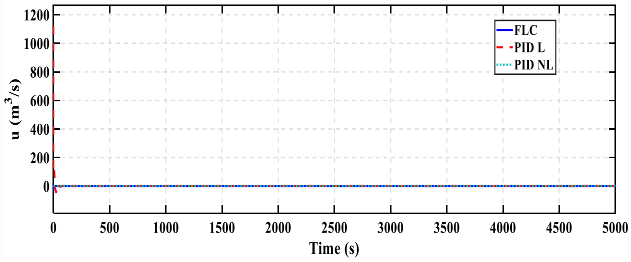
(a) Closed view of region between (0-10000) seconds



(b) Closed view of region between (0-10) seconds



(c) Closed view of region between (0-100) seconds

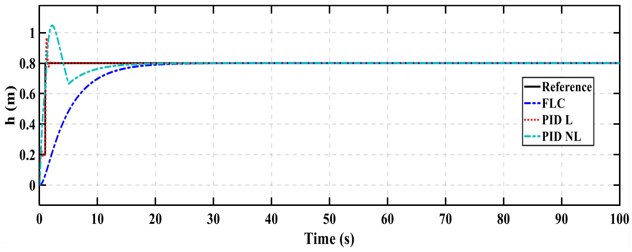


(d) Closed view of region between (0-5000) seconds

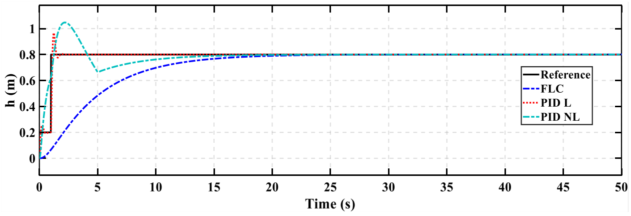
Fig. 15. Control action of single Tank in run 2

When used coupled tanks and applied FLC PID L and PID NL, the following results obtained in run 1 when desired point or height desired equal 0.8 m, and in run2 equal to 1 m as illustrated in Fig. 16 to Fig 25.

The coupled tank system involves two interconnected tanks where the liquidity level in one tank influences the other, making the kinetics more complex compared to a single tank system. The mathematical model is second-order, with the flow between the tanks governed by resistances and capacitances. Equations describe how the inflow and the difference in liquid levels between the tanks influence the system. This system's complexity requires advanced controllers with SMC and FLC to handle nonlinearities and interactions. Simulations exhibit that FLC and SMC superior public presentation in stabilizing the coupled system, highlight their potency for this more intricate setup.

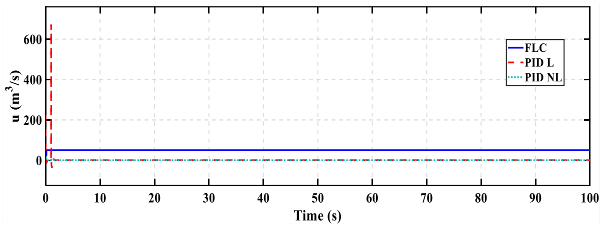


(a) Closed view of region between (0-100) seconds

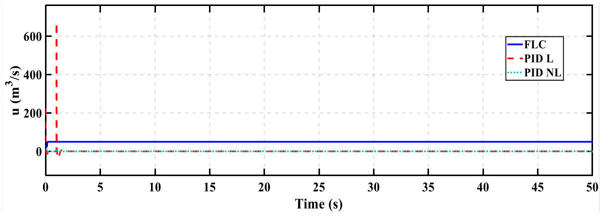


(b) Closed view of region between (0-50) seconds

Fig. 16. Run 1 analysis of coupled tank liquid level system (Desired Point = 0.8 m)

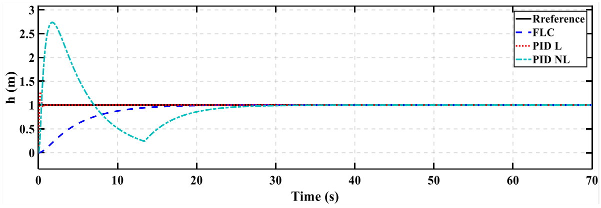


(a) Closed view of region between (0-100) seconds

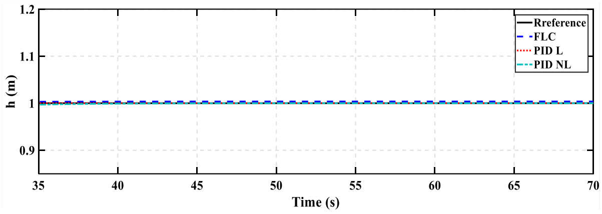


(b) Closed view of region between (0-50) seconds

Fig. 17. Control action of coupled Tank in run 1

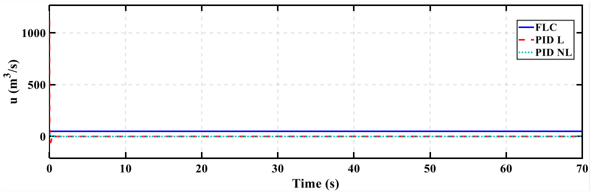


(a) Closed view of region between (0-70) seconds

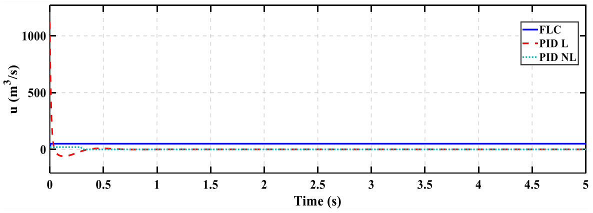


(b) Closed view of region between (35-70) seconds

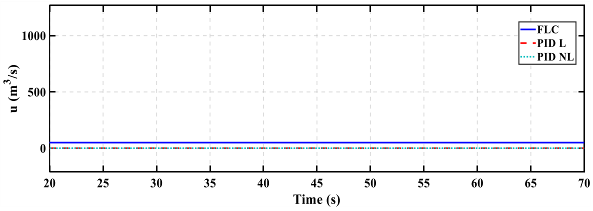
Fig. 18. Run 2 analysis of coupled tank liquid level system (Desired Point = 1 m)



(a) Closed view of region between (0-70) seconds



(b) Closed view of region between (0-5) seconds



(c) Closed view of region between (20-70) seconds

Fig. 19. Control action of coupled Tank in run 2

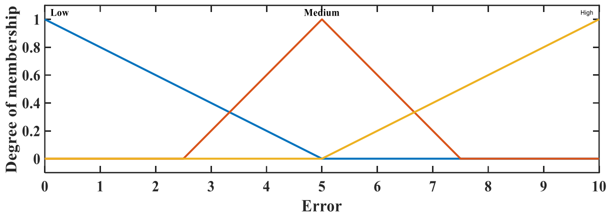


Fig. 20. Input membership function of error

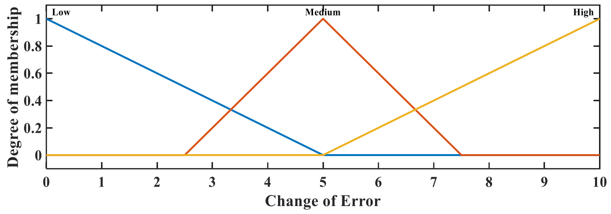


Fig. 21. Input membership function of change in error

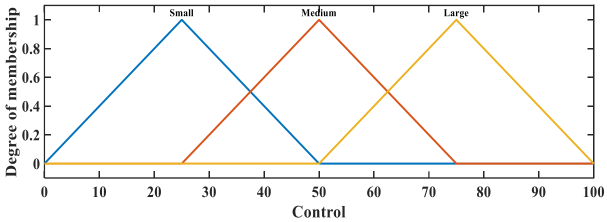


Fig. 22. Output membership function

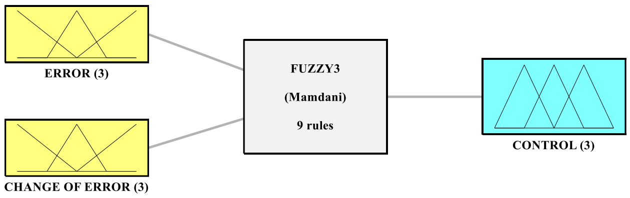


Fig. 23. Fuzzy Logic Control System Diagram

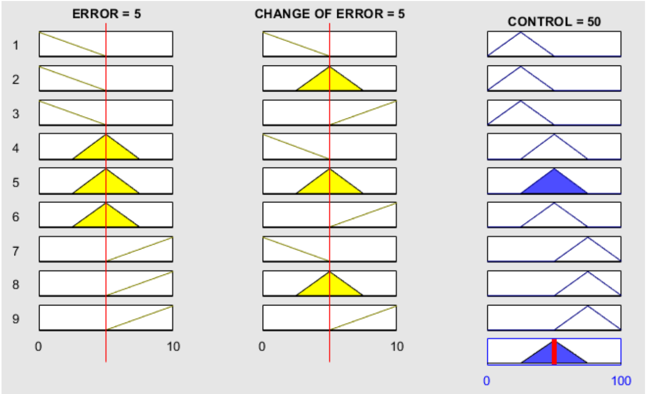


Fig. 24. Fuzzy inference system block diagram

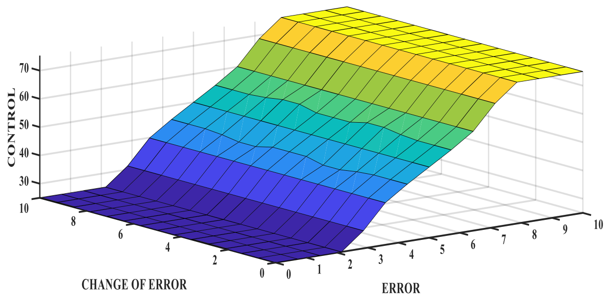


Fig. 25. Control surface of the FLC

The number of rules equal 9 of FLC for coupled tanks liquid level system. Here some of them:

If (ERROR is Low) and (CHANGE OF ERROR is Low) then CONTROL is Small (1).

If (ERROR is Medium) and (CHANGE OF ERROR is Low) then CONTROL is Medium (1).

If (ERROR is High) and (CHANGE OF ERROR is Low) then CONTROL is Large (1).

Table V provides a concise comparison of the performance of FLC in controlling the fluid height in a coupled tanks system, highlighting key observations from runs 1 and 2.

TABLE V. THE SUMMARIZED ANALYSIS OF COUPLED TANKS LIQUID LEVEL SYSTEM RUN1 AND RUN 2

Criteria	**Run 1**	**Run 2**
Control Accuracy and Precision	- Height *h* maintained closely around desired level	
	- FLC effectively handles nonlinearities and interactions	
	- Narrow range of height *h* around setpoint	
Stability and Oscillation	- Minimal oscillation around setpoint	
	- More deviation compared to Run 2	- Stabilizes quicker with less deviation compared to Run 1
		- Indicates improvement/adaptation in control strategy
Comparative Performance with PID	- Superior control with less overshoot and quicker stabilization compared to PID controllers	
Summary	- Demonstrates excellent precision, stability, and responsiveness of FLC in managing fluid levels in coupled tanks	

B. *Results of 4th Controller i.e., SMC*

Now, by using SMC for single tank with desired level equal to 0.8 m. The controllers' parameters are in Table VI. The following results in Fig. 26 to Fig. 31 obtained for run 1.

TABLE VI. CONTROL PARAMETERS

Parameter	**Value**
α	1
k	600
ϵ	0.1

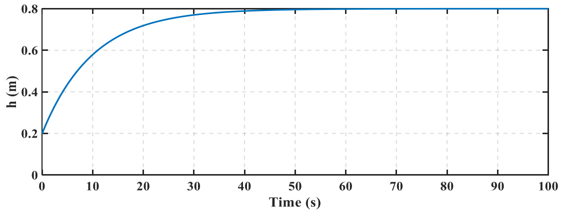


Fig. 26. Liquid level in Tank based SMC in run 1 of single Tank (Desired Point = 0.8m)

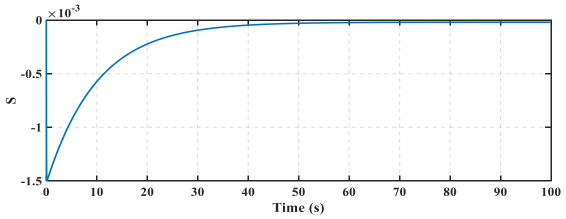


Fig. 27. Sliding surface-based SMC in run 1 of single Tank (Desired Point = 0.8m)

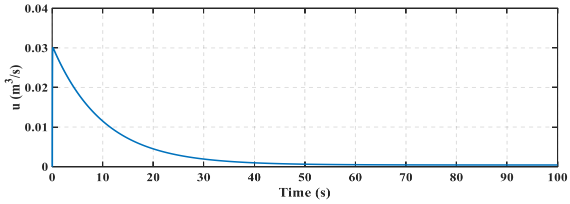


Fig. 28. control signal-based SMC in run 1 of single Tank (Desired Point = 0.8m)

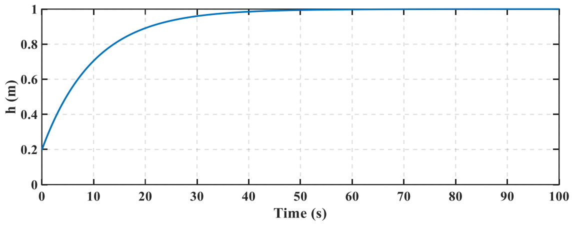


Fig. 29. Liquid level in Tank based SMC in run 2 of single Tank (Desired Point = 1m)

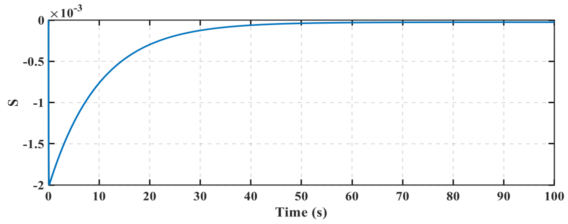


Fig. 30. Sliding surface-based SMC in run 2 of single Tank (Desired Point = 1m)

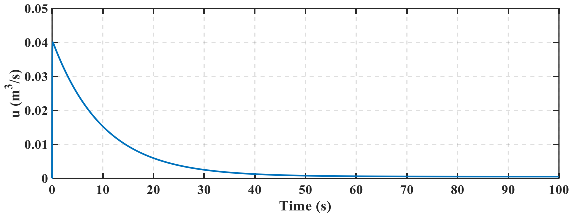


Fig. 31. Control signal-based SMC in run 2 of single Tank (Desired Point = 1m)

The same of single tank of SMC, now applying SMC for coupled tanks with desired level equal to 0.8 m and based on the controllers' parameters in Table 6 the following results in Fig. 32 to Fig. 35 obtained for run 1.

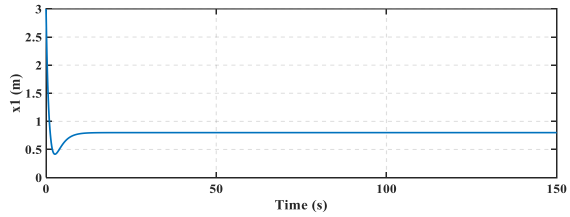


Fig. 32. Liquid level (x_1) in Tank based SMC in run 1 of coupled Tank (Desired Point = 0.8m)

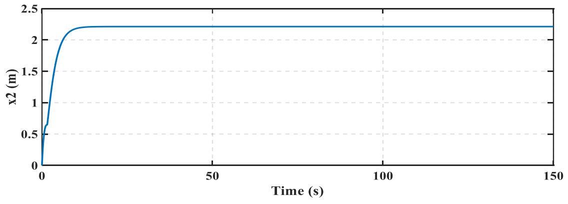


Fig. 33. (x_2) based SMC in run 1 of coupled Tank (Desired Point = 0.8m)

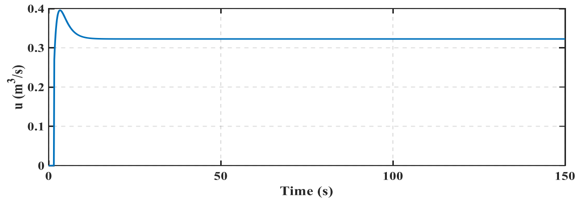


Fig. 34. Control signal-based SMC in run 1 of coupled Tank (Desired Point = 0.8m)

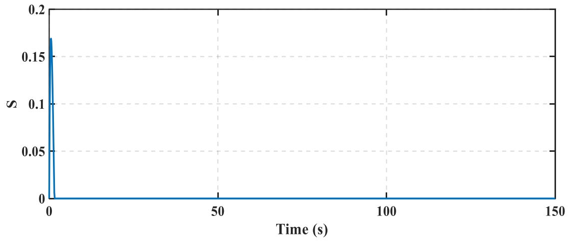


Fig. 35. Sliding surface-based SMC in run 1 of coupled Tank (Desired Point = 0.8m)

In run 2 suppose the desired level equal 1m, Fig. 36 to Fig. 39.

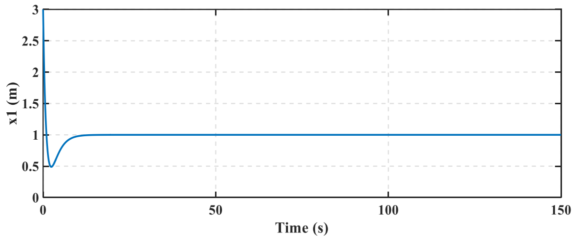


Fig. 36. Liquid level (x_1) in Tank based SMC in run 2 of coupled Tank (Desired Point = 1 m)

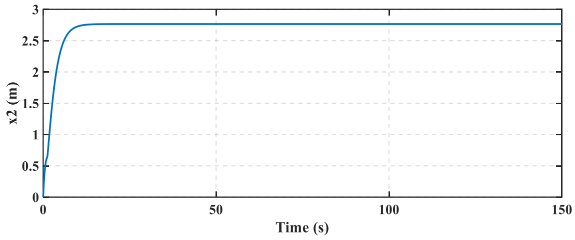


Fig. 37. (x_2) based SMC in run 2 of coupled Tank (Desired Point = 1 m)

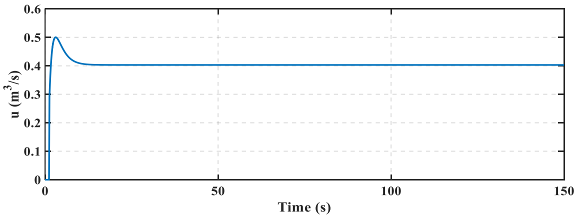


Fig. 38. Control signal-based SMC in run 2 of coupled Tank (Desired Point = 1 m)

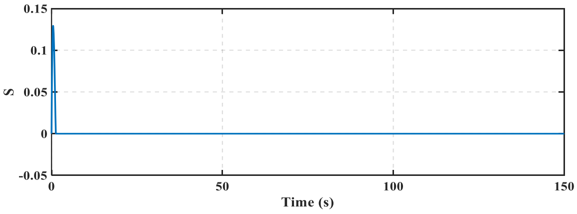


Fig. 39. Sliding surface-based SMC in run 2 of coupled Tank (Desired Point = 1 m)

Summary comparison between run 1 and run 2 of single and coupled-tank liquid level system-based SMC illustrated in Table VII.

TABLE VII. SUMMARY COMPARISON BETWEEN RUN 1 AND RUN 2 OF SINGLE AND COUPLED-TANK LIQUID LEVEL SYSTEM-BASED SMC

System	Aspect	Run 1 and Run 2
Single Tank SMC	Control Strategy and System Response	SMC maintains h close to the desired level, driving the system state towards ss.
	Robustness and Overshoot	Minimal overshoot, rapid correction of deviations, robust against model uncertainties.
Coupled Tanks SMC	Control Action and Sliding Surface	Rapid switching of u, maintains states within ss, potential increased mechanical wear.
	Performance Over Time	Consistent performance, effective initial tuning, crucial for long-term reliability.
Overall Summary		Demonstrates robustness, quick response, stability.

C. Comparison All the Suggested Controller

Table VIII presents a comparative analysis of four control methods—Sliding Mode Control (SMC), Fuzzy Logic Control (FLC), Linear PID (PID L), and Nonlinear PID (PID NL)—used in single and coupled tank systems. Each method's performance is evaluated based on settling times and desired liquid levels. SMC is robust but not the quickest, excelling in complex coupled systems. FLC offers the fastest response, making it highly suitable for both single and coupled systems. PID L performs surprisingly well in coupled tanks but is slower in single tanks. PID NL struggles with long and inconsistent settling times, indicating poor tuning. The choice of control method should consider system complexity and response speed, with FLC being the most versatile and SMC reliable for complex environments Fig. 40 and Fig. 41: performance analysis of single and coupled tanks in SMC, FLC, PID L, and PID NL systems in Run 1 and Run 2.

From the data provided in the Table VIII, FLC is the fastest and arguably the best controller in terms of settling time for both single tank and coupled tank systems. Specifically: In single tank settings, the FLC achieved a settling time of 8.34 seconds in run 1 and a remarkably rapid 1.088 seconds in run 2. In coupled tank settings, the FLC also performed efficiently with settling times of 31.015 seconds in run 1 and 6.071 seconds in run 2.

These results demonstrate that FLC not only stabilizes the system faster than the other controllers tested SMC, PID L, and PID NL but also shows consistent performance across different scenarios and setups. This makes it a superior choice for applications requiring rapid response and stability in liquid level control systems.

Validation of Theoretical Models: These simulation results formalize the theoretical models by demonstrating how each control strategy performs below real-world conditions. The FLC and SMC controllers provided the best balance of precision and speed, positive their effectiveness in dominant non-linear and coupled systems as expected in the theoretical analysis.

TABLE VIII. COMPARISON OF ALL CONTROLLERS SUGGESTED IN BOTH SINGLE AND COUPLED-TANK IN RUN1 AND RUN2

Method Type		SMC		FLC		PID L		PID NL	
		settling time (second)	Desired Liquid Level Or Goal point 0.8 m for run 1 and =1 m for run 2	settling time (second)	Desired Liquid Level Or Goal point 0.8 m for run 1 and =1 m for run 2	settling time (second)	Desired Liquid Level Or Goal point 0.8 m for run 1 and =1 m for run 2	settling time (second)	Desired Liquid Level Or Goal point 0.8 m for run 1 and =1 m for run 2
Single Tank	run 1	99.61	0.8	8.34	0.8	182.24	0.8	9804.506	0.8
	run 2	99.6	1	1.088	1.013	134.957	1	3591.178	1
Coupled Tank	run 1	23.17	0.7999	31.015	0.8	6.823	0.8	36.289	0.8
	run 2	25.93	0.9999	26.071	1	1.681	1	51.187	1

The simulation figures and tables (e.g., Table IV and V) offer decimal proof of the system's response time, accuracy, and stability, which directly support the theoretical models discussed in the paper.

In summary, the simulations provide comprehensive validation of the theoretical models, highlighting the strengths of FLC and SMC in practical applications.

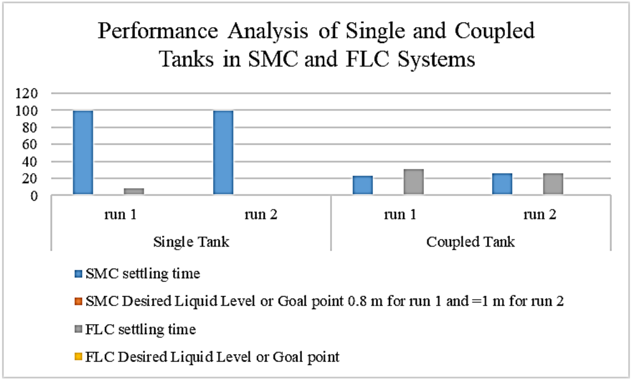


Fig. 40. Performance analysis chart of single and coupled tanks in SMC and FLC systems in run1 and run 2

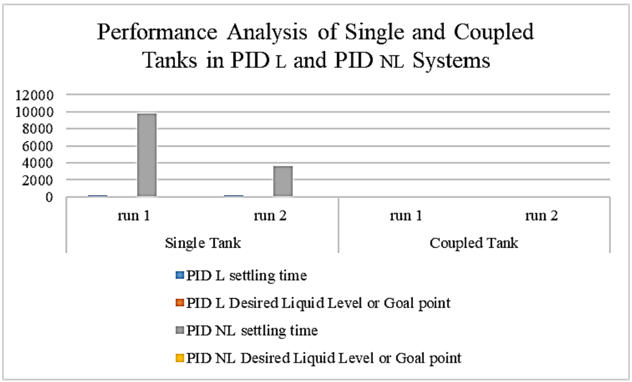


Fig. 41. Performance analysis of single and coupled tanks in PID L and PID NL systems in run1 and run 2

Table IX summarizes the key limitations identified in the study and contextualizes them within the framework of relevant present literature. It highlights the areas where the study could be cleared and provides insights into how the findings relate to similar research conducted in this field. Each limitation is paired with a contextualization to illustrate the relevancy and bear on futurity work.

TABLE IX. LIMITATIONS AND CONTEXTUALIZATION OF THE STUDY

Aspect	**Limitations and Contextualization**
Scope of Application	The study is limited to single and coupled tank systems.
Controller Types	The controllers tested (FLC, PID, SMC)

Table X presents a comparative analysis of the performance of different control strategies, including FLC, PID, Nonlinear PID, and SMC. The comparison focuses on the current study and previous studies for context. This comparison highlights the improvements and contributions made by the current study in control performance.

V. CONCLUSIONS

This paper on intelligent controllers for liquid-level systems demonstrates significant public presentation improvements, reduction oscillations and speeding up subsidence times compared to conventional controllers. The FLC in particular, optimized system stability, achieving rapid stabilization inside seconds. As seen in the provided data, the FLC reaches a steady-state level in as little as 8.34 seconds in Run 1 and 1.088 seconds in Run 2 for the single-tank system. Similarly, the SMC stabilizes the system in approximately 23.17 seconds in the coupled tank system, reflecting its robust control capabilities. These intelligent systems excel in precision, efficiency, and adaptability, importantly enhancing mechanization by eliminating manual adjustments. By comparison SMC, FLC, PID L, and PID NL in versatile configurations, key findings include: SMC: demonstrated hardiness in complex setups, FLC: Showed fast and undefined responses in some single and coupled-tank systems. Also, PID L: performed better than expected in specific contexts. PID NL: Struggled with undefined in intricate configurations. This study emphasizes the grandness of tailored control strategies to heighten system public demonstration and stability, impacting industries like manufacturing and chemical processing. some limitations include the focus on one and coupled-tank systems, with other scenarios left for future research.

TABLE X. COMPARISON OF CURRENT STUDY WITH OTHER STUDIES AND LIMITATIONS

Aspect	Current Study	Study [3] Limitations	Study [77] Limitations	Study [78] Limitations
Controller Performance	FLC offers the quickest response and improve preciseness for single and linked tanks, demonstrating high efficiency.	Hybrid controllers tested, but the study did not focus on individual controller public presentation (FLC alone).	Focused heavily on PID controllers, which perform poorly in nonlinear systems and time-varying environments.	Emphasis on SMC's robustness but limited exploration of reply time or comparison with unusual controllers.
Focus on Nonlinear Systems	Provides a comprehensive examination analysis of FLC, PID, Nonlinear PID, and SMC in nonlinear environments, showing FLC’s superiority.	express discussion on nonlinear systems and performance of individual controllers in handling them.	Study did not adequately turn to the limitations of PID controllers in nonlinear or complex system dynamics.	The contemplate lacked a detailed comparison of controllers’ performance in nonlinear systems.
Simulation Data	Detailed simulation results with specific metrics for undefined (settling time, precision, stability, etc.).	Results were more theoretical with limited simulation or real-time data for performance analysis.	Heavily theoretical; no specific simulation results comparing dual controllers in detail.	Simulation data focused on SMC, lacking comprehensive comparison with other controllers like FLC or PID.
Controller Robustness	Demonstrates the lustiness of SMC patc highlighting FLC’s faster response, making it suited for more applications	Express robustness analysis, focusing more on hybrid systems and lacking in-depth study of FLC’s robustness.	Focused mainly on PID’s simpleness but neglected robustness challenges in complex, nonlinear systems.	Robustness of SMC was discussed, but FLC’s superior performance in adaptability and precision was unnoticed.
Comprehensive Comparison	comprehensive examination comparison of four controllers (FLC, PID, Nonlinear PID, SMC) in both single and coupled systems.	Lack of a comprehensive performance undefined crosswise different restrainer types (FLC, PID, SMC, etc.).	Limited to PID controller performance, neglecting advanced alternatives like FLC or SMC.	Focused solely on SMC; did not explore FLC or other controllers for better reply times or adaptability.
Real-World Application	Provides insights into industrial applications, reducing stuff waste and increasing efficiency in real-time scenarios.	Limited discussion on industrial implications and practical benefits of advanced controllers like FLC.	Lacked practical real-world implications for liquidness tear down systems, especially in nonlinear environments.	Focused on theoretical and simulation results with little attention to industrial application benefits.

VI. FUTURE WORK SUGGESTIONS

Enhanced adaptive control mechanisms using machine learning, multi-objective optimization for balancing performance criteria, and improved robustness against disturbances wish be explored. Additionally, real-time testing through Hardware-in-the-Loop and the practical application of hybrid controllers in more complex systems will be considered. These future directions will help extend the study's impact and improve control strategies in industrial applications. Future work could involve exploring more undefined multi-tank systems and incorporating adaptive control strategies. A promising direction for future research is the exploration of hybrid control approaches, such as combining FLC with SMC or PID to enhance system adaptability and robustness.

Nomenclature

A is the Cross-sectional area of the tank, m^2

C is the Capacitance of the tank, $\mathrm{m}^3/_{\mathrm{m}}$

D is the Diameter of the tank, m

h is the Height of the tank, m

Q_o is the Maximum liquid flow, $1/_{\mathrm{s}}$

Q_o is the Maximum liquid flow, $\mathrm{m}^3/_{\mathrm{s}}$

R is the Resistance, $\mathrm{s}/_{\mathrm{m}^2}$

V is the Volume of the tank, m^3

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