Fuzzy PID Controller Design for a Coupled Tank Liquid Level Control System

MUSTAFA SAAD, MUAD ALSHARA, KHALED MUSTAFA
Control Engineering Department,
College of Electronic Technology/Bani Walid,
Bani Walid, Libya,
LIBYA

Abstract: - In industrial processes, the most important loop is the liquid-level control loop. The coupled tank system CT-100 becomes an essential apparatus for process control researchers. This paper introduces two controller techniques to control the water level in the second tank as a single input single output system. The PID controller is designed to control the linearized model, where the controller parameters are tuned using the Ziegler- Nichols tuning method. In addition, Fuzzy PID is designed based on adequate knowledge and experience. The proposed control approaches are simulated using MATLAB Simulink. Then, the obtained results using these controllers are compared in terms of time response specifications and the ITAE criterion. It is also, tested for step-change tracking signal and disturbance rejection. Finally, the simulation results showed that the Fuzzy PID controller has a robust performance.

Key-Words: - Couple tank system, Level control, PID, Ziegler-Nichols, Fuzzy PID

Received: January 14, 2023. Revised: September 16, 2023. Accepted: October 20, 2023. Published: November 15, 2023.

1 Introduction

Many process control systems like industrial applications are concerned with level control. Some of these processes are single-loop or multi-loop level control. In process industries, such as the interaction between the tanks, level control is one of the important process-controlled variables, [1]. Some of the industrial applications depend on level control. In chemical industries, Evaporators exist in many chemical industries for separating products. While the liquid level control is an essential loop in an evaporator. For example in a fertilizer process plant, the evaporator is used to transform a weak solution of chemicals into a more concentrated solution. The level of the solution and the pressure of the evaporator have to be controlled to get the required concentration, [2].

PID controllers are common practice in industrial process control. In a study, more than 11,000 controllers are used in process industries and 97% of controllers are PIDs controllers, [3]. The simplicity and good performance make the PID controller very popular and this lets engineers operate it more easily. The PID controller gains can be chosen based on the trial and error method or other tuning methods such as the tuning rules offered by Ziegler-Nichols.

Zadeh originally proposed fuzzy logic in 1965. This theory is based on fuzzy sets with degrees of membership ranging between 0 and 1, challenging the traditional set theory. In 1974, Mamdani developed the first fuzzy control applied to a steam engine. The miniaturization and power of digital electronics nowadays allow for the implementation of fuzzy logic in compact and reliable controllers, [4]. In modern control systems, fuzzy logic control becomes an excellent choice due to its flexibility and simplicity of application. It has been used in many house and industrial applications, for example in rice cookers, air conditioners, and process industries. Last, the fuzzy logic controller has challenged other control design methods. Even though PID control is the largest used control structure in the process of manufacturing. The fuzzy logic controller has great importance as it offers flexibility in design, can model complex and nonlinear systems, and ease of application for complex systems. These features were not found in the classical control design approaches, [5].

Many research studies with different control schemes to control the level of liquid of the coupled tank system have been controlled, [1], [2], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15]. A fuzzy logic controller is one of the control schemes used to control the liquid level of a nonlinear-coupled tank system, [16], [17], [18].

2 Mathematical Model of Coupled Tanks System

The schematic diagram of the coupled-tank system CTS-100 system is shown in Figure 1. The internal baffle can vary the flow rate between the tanks. The opening outlet of the two tanks is adjusted using adjustable clamps.

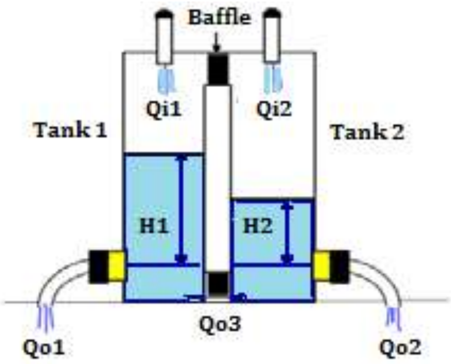

Fig. 1: Schematic diagram of the coupled tank system.

This research aims to control the liquid level in the second tank by adjusting the manipulation in the first tank. The linear model equations which are derived from the nonlinear model of the coupled tank system as stated in the previous work, [11], can be written as follows

$$A_1 \frac{dh_1}{dt} = q_1 - \frac{\alpha_1}{2\sqrt{H_1}} h_1 - \frac{\alpha_3}{2\sqrt{H_1 - H_2}}(h_1 - h_2) \quad (1)$$

$$A_2 \frac{dh_2}{dt} = q_2 - \frac{\alpha_2}{2\sqrt{H_2}} h_2 + \frac{\alpha_3}{2\sqrt{H_1 - H_2}}(h_1 - h_2) \quad (2)$$

Where
H_1, H_2 = steady-state height in tank1 and tank2 respectively.
A_1, A_2 = cross-sectional area of tank1 and tank2 respectively.
q_1, q_2 = pump flow rate into tank1 and tank2 respectively.

The pump actuator dynamic is considered an important control element in the plant and can be modeled in the first-order linear differential equation in the following equation.

$$T_c \frac{dq_i(t)}{dt} + q_i(t) = q_c(t) \quad (3)$$

Where
T_c is the pump time constant.
$q_i(t)$ is a time-varying input flow rate.
$q_c(t)$ is the commanded flow rate.

The plant transfer function describes the relationship between the controlled variable h_2 (Level height at the second tank) and the manipulated variable q_1 become. The value of the system parameters is obtained from, [12].

$$\frac{h_2(s)}{q_1(s)} = \frac{3.98 \times 10^{-3}}{s^2 + 0.41s + 0.0257} \quad (4)$$

Also, the actuator dynamic transfer function of the first tank

$$\frac{q_1(s)}{q_c(s)} = \frac{13.571}{s+1} \quad (5)$$

3 Controllers Design for Water Level Control of Coupled Tank System

The controller's design objective is to meet the required performance of the transient and steady-state response specifications. This section discusses two design control techniques: PID controller and Fuzzy PID controller.

3.1 PID Controller Design

A PID controller is one of the feedback controller types whose output, an actuating signal u(t), generally depends on the error signal e(t). Which is the difference between the desired set point and the measured output variable. Conventional PID controllers have been widely applied in industrial applications, [19]. The common equation is expressed in Eq. (6) which consists of three terms proportional, integration, and a derivative term.

$$\frac{U(s)}{E(s)} = K_c\left(1 + \frac{1}{T_i s} + T_d s\right) = K_p + \frac{K_i}{s} + K_d s \quad (6)$$

The first Ziegler-Nichols technique is found using frequency response analysis, [20]. The principle is to obtain the ultimate gain K_u, this gain can be determined directly from the Bode plot magnitude curve of the system transfer function. When the magnitude curve crosses the 0 dB line, the ultimate gain can be determined by the following equation.

$$K_u = 10^{\left(|G(j\omega_\pi)|/20\right)} \quad (7)$$

Where
ω_π is the frequency at the phase curve crosses the -180° line.

The frequency corresponding to the ultimate point is known as the oscillation frequency ω_π. This point is characterized by two parameters defined as the ultimate gain K_u and ultimate period T_u. The ultimate period T_u can be determined as

$$T_u = \frac{2\pi}{\omega_\pi} \quad (8)$$

On the other hand, the Ziegler-Nichols tuning method is based on adjusting a closed loop until steady oscillations occur. This requires increasing the proportional gain K_p until the oscillation response occurs with constant amplitude, while derivative and integral controller gains are set to zero. The value of the proportional gain that yields constant oscillations is called the ultimate gain K_u and the period of this oscillation is called the ultimate period T_u. Using the value of $K_u$and T_u Ziegler - Nichols prescribes the following values of K_c, T_i, and T_d of the controller as shown in Table 1.

Table 1. PID controller parameters using Ziegler-Nichols

Controller Type	Proportional Gain K_c	Integral Time T_i	Derivative Time T_d
PID	$K_u/1.7$	$T_u/2$	$T_u/8$

The frequency response data (Bode plot) of the open-loop transfer function of the coupled tank system $h_2(s)/q_c(s)$ is shown in Figure 2.

It is clear that, from the Bode plot, the magnitude is $-20.7\,dB$ and the oscillation frequency is $0.657 rad/sec$. Using Eq (7) and (8), the ultimate gain and ultimate period are 10.839 and $9.563 sec$ respectively.

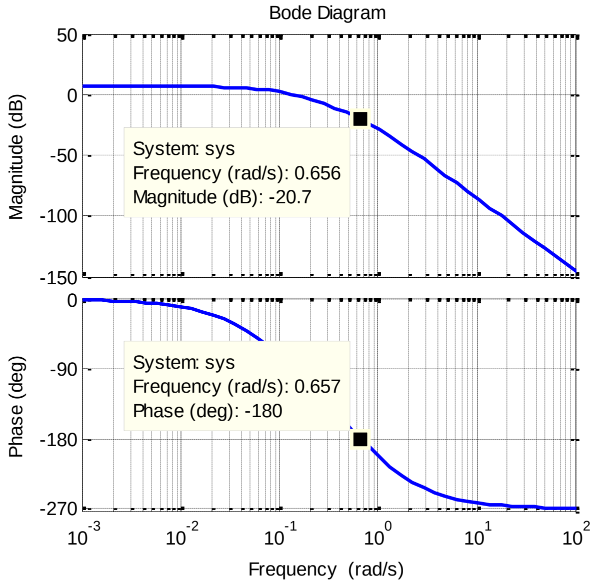

Fig. 2: Bode plot response of coupled tank system.

The PID controller parameters are determined based on formulas in Table 1. The obtained output response using these parameters has a high oscillation, and high overshoot, and takes a long time to reach a steady state. Therefore, a few refined tunes were done on these parameters to enhance the system response and the best PID controller parameters were $K_P = 6.4$, $K_i = ,1.43$ and $K_d = 7.623$.

3.2 Fuzzy PID Controller Design

A general fuzzy controller model or a well-known fuzzy inference system (FIS) structure is shown in Figure 3. The fuzzification involves the conversion of the input numbers into several fuzzy variables with appropriate fuzzy sets, memberships function, and universe of discourse. Then, the inference mechanism provides the mechanism for referring to the rule base such that the appropriate rules are fired. The core of the knowledge base is the definition of the linguistic if-then rules of the Mamadani type, [20]. After that, the aggregation process is done by aggregating the outputs of all rules and combining them into a single fuzzy set. In the end, the defuzzification process converts an output fuzzy set into a crisp value. Many defuzzification methods have been proposed in recent years. Such as centroid, mean-max, max membership, and weight average methods. Centroid is the most prevalent and physically appealing of all the defuzzification methods.

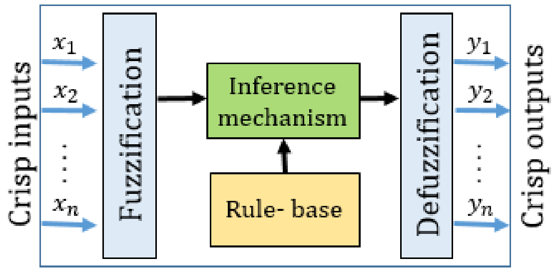

Fig. 3: Fuzzy controller.

In this paper, the suggested fuzzy controller consists of two input variables: error (E) and rate of change of error (CE). These variables are quantized into five fuzzy sets NL, N, Z, P, and PL that respectively represent Negative Large, Negative, Zero, Positive, and Positive Large. The fuzzy controller contains three output variables which are proportional fuzzy (K_{pf}), integral fuzzy (K_{if}), and derivative fuzzy (K_{df}). Each output variable is quantized to five fuzzy sets labeled as QS (Quite Small), S (Small), M (Medium), L (Large), and QL (Quite Large). In the universe of discourse of the first input, the error variable is chosen based on measuring the maximum and minimum values of the error signal and for the second input, the change of error is selected to be one-tenth of the error input. The universe of discourse of each output variable is chosen based on the best values of the PID controller K_{Pf} from 0 to 6.4, K_{if} from 0 to 1.43, and K_{df} from 0 to 7.623. Figure 4 shows the membership functions of input variables. While the universe discourse of input variables is scaled as follows: E =30 and CE=3. The membership functions of the output variables are shown in Figure 5.

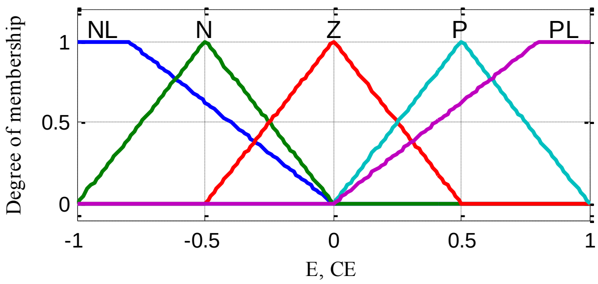

Fig. 4: Membership functions of input variables E and CE.

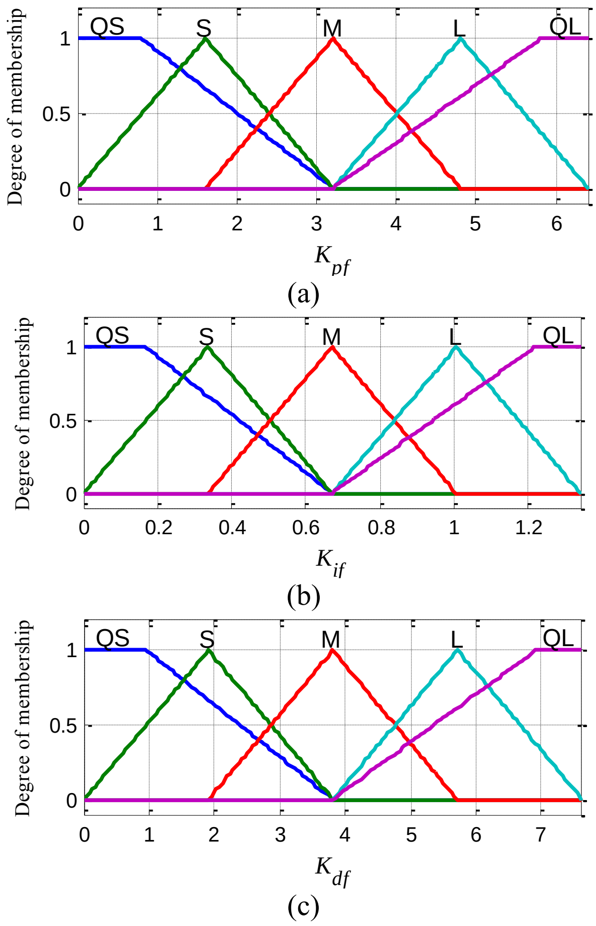

Fig. 5: Membership functions of output variables (a) Kpf, (b) Kif, and (c) Kdf.

The most widely used structure in the formulation of fuzzy inference rules is based on experience and control engineering knowledge. In this paper, Mamadani-type FIS is used. Table 2 illustrates the suggested fuzzy rules, which are 25 rules for each output variable. The fuzzy output for each output variable is obtained using Max-Min composition and by applying the centroid defuzzification method, the crisp output values of the fuzzy controller K_{Pf}, K_{if}, and K_{df} are calculated.

Table 2. Fuzzy controller rule base of the system.

		CE				
		NL	N	Z	P	PL
E	NL	QS	QS	QS	S	M
	N	QS	QS	S	M	L
	Z	QS	S	M	L	QL
	P	S	M	L	QL	QL
	PL	M	L	QL	QL	QL

The suggested Fuzzy PID controller as shown in Figure 6 is basic PID and the FLC structure. The basic PID controller is designed based on the linear model of the liquid-level process of the coupled-tank system. Hence, the best parameters of the PID controller are used as initial parameters K_{p0}, K_{i0}, and K_{d0} of the basic PID controller. Hence, the fuzzy PID controller parameters are calculated by the following equations:

$$K_P = K_{pf} + K_{p0}$$
$$K_i = K_{if} + K_{i0,}$$
$$K_d = K_{df} + K_{d0}$$

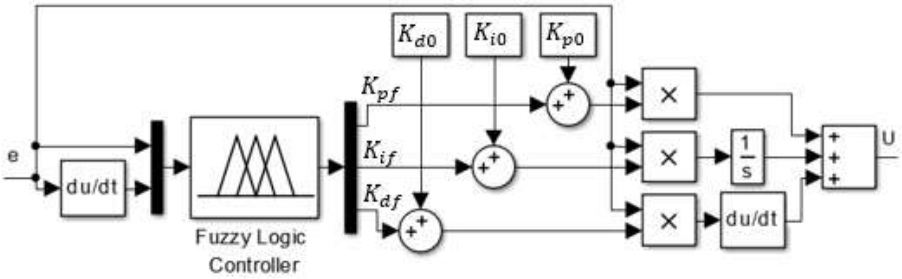

Fig. 6: Structure of fuzzy PID controller.

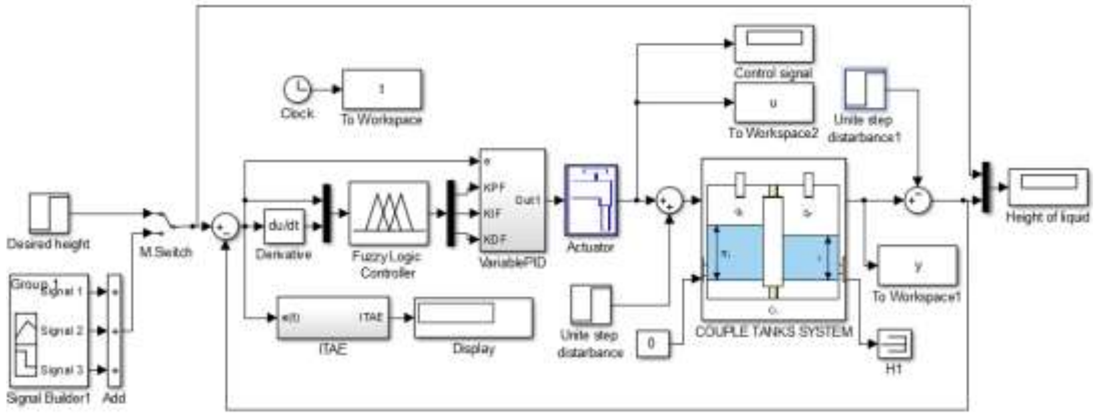

Fig. 7: Simulink block diagram to control the level height of tank 2 using a Fuzzy PID controller.

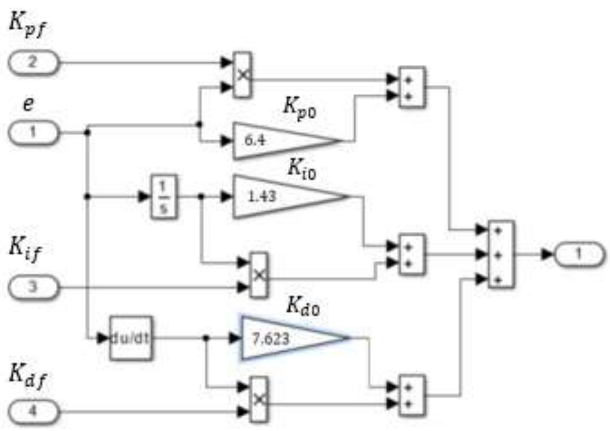

Fig. 8: Simulink of variable PID.

4 Simulation Results and Discussions

The output results of the designed control techniques that have been proposed in this paper are analyzed and compared with each other in this section. Specifically, the Simulink block diagram to control the level height of tank 2 using a Fuzzy PID controller is presented in Figure 7. Similarly, the Simulink depiction of variable PID is presented in Figure 8. Moreover, the Step responses of liquid level in tank2 are plotted for two controllers on the same window, to see more comparison between controllers' performance. Figure 9 shows the output responses using PID and Fuzzy PID controller for the 9 cm desired level height in tank 2.

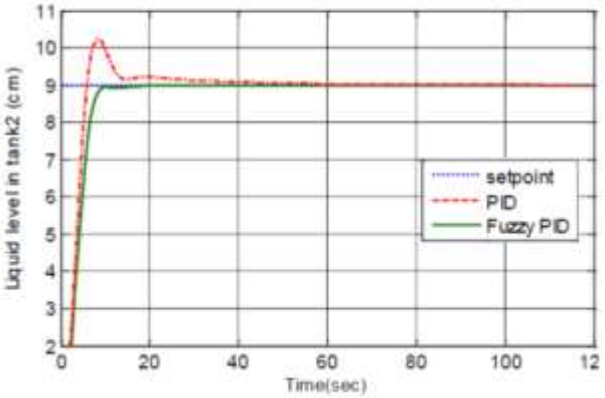

Fig. 9: Output responses using PID and Fuzzy PID controller.

The response with the Fuzzy PID controller has no overshoot compared to the PID controller response, which has a 12% overshoot. However, both responses have zero steady-state error, the response using Fuzzy PID has a smaller settling time of 8.56 seconds compared with 23.28 seconds using the PID controller. Even, the response using the PID controller is faster than the response using Fuzzy PID. The ITAE criteria of the Fuzzy PID controller were smaller than the PID controller. The performance characteristics of the level height in tank 2 using PID and Fuzzy PID controllers are summarized in Table 3.

Table 3. Performance specification using PID and Fuzzy PID controllers.

Performance specifications	PID	Fuzzy PID
Settling time (second)	23.28	8.56
Overshoot (%)	12	0
Peak time (second)	8.45	-
Steady-state error	0	0
ITAE	315.1	139.4

The setpoint change was performed at 100 seconds by a magnitude of 15 cm height in water level and at 200 seconds is changed again by a magnitude of 6 cm in water level height.

The setpoint-tracking test involved changing the setpoint through the operation as shown in Figure 10. Both approaches exactly tracked the reference input.

The controlled system is tested with disturbance in liquid deficiency. The disturbance is introduced by decreasing the amount of liquid flow rate for tank 2 by an amount of 2 cm^3 /sec at a time of 80 sec. The responses of the coupled tank system under the effect of disturbance are shown in Figure 11.

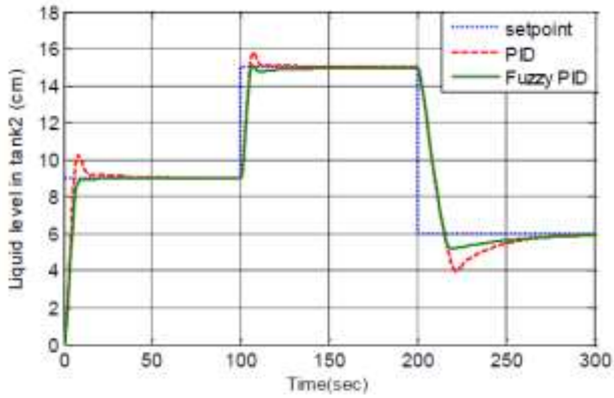

Fig. 10: Setpoint tracking the performance of the system

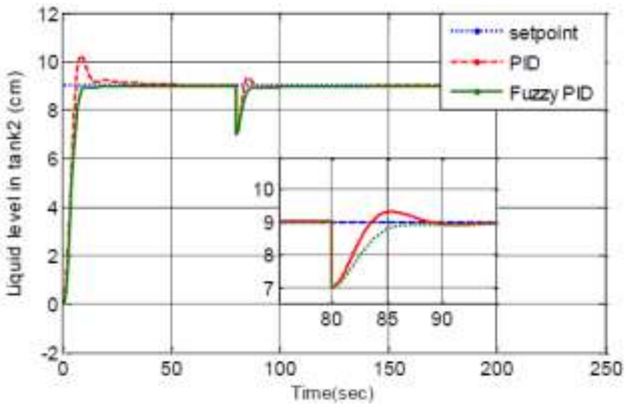

Fig. 11: Responses of PID and FPID controllers in the presence of disturbance with -2 cm^3 /sec.

The PID controller takes approximately 145 seconds for the system to return to the commanded setpoint. The Fuzzy PID Controller takes a minimum effort to reject the effect of disturbance compared to the PID controller and a shorter time with 105 seconds in the presence of disturbance. The performance index using a Fuzzy PID controller is 769 compared to 941.3 using a PID controller.

5 Conclusions

In this paper. The PID controller is designed properly for the linearized model of the coupled tank system. Where, the controller parameters are tuned using the Ziegler-Nichols method, which gives oscillation in the response shape and high overshoot for the first trial. Then, the trial and error method is used, until the best responses are obtained by using this controller. The PID controller is tested for step-tracking input and disturbance input. It can be concluded that the PID controller has tracked the setpoint change for the linear model and reached the steady-state value in each change. For the disturbance rejection, the designed PID controller approved its ability to reject this effect a few times.

The designed Fuzzy PID controller combines the advantages of the fuzzy logic controller and PID controller. In this research, the outputs of fuzzy controllers become a function of the PID controllers. Hence, any change in the error will cause a change in the controller parameters. Therefore, this method resulted in a zero overshoot and the fastest.

Simulation results showed the success of the proposed method, where the system responses using Fuzzy PID and conventional PID controller have good performance in transient response, steady-state response, step tracking signal, and disturbance rejection. So, the performance measure ITAE is used in this research to assist in choosing the best controller performance. In conclusion, it can be concluded that the Fuzzy PID controller is robust and attains excellent control performance as compared to the PID controller.

References:

[1] A. H. Y. Yacoub, S. Buyamin, and N. A. Wahab, Integral Time Absolute Error Minimization For PI Controller On Coupled Tank Liquid Level Control System Based On Stochastic Search Techniques, *Jurnal Teknologi*, pp. 381-402, 2011.

[2] M. SAAD and A. RAMADHAN, Sliding Mode Control of Nonlinear Coupled Tank System, *WSEAS Transactions on Systems*, ISSN / E-ISSN: 1109-2777 / 2224-2678, Volume 18, 2019, Art. #5.

[3] K. J. Åström and T. Hägglund, Revisiting the Ziegler–Nichols step response method for PID control, *Journal of process control*, vol. 14, no. 6, pp. 635-650, 2004, doi: 10.1016/j.jprocont.2004.01.002.

[4] C. Urrea and F. Páez, Design and Comparison of Strategies for Level Control in a Nonlinear Tank, *Processes*, vol. 9, no. 5, p. 735, 2021, doi: https://doi.org/10.3390/pr9050735.

[5] M. Ahsan and M. U. Khalid, Liquid Level Control of a Nonlinear Coupled Tanks System using Fuzzy Logic Control, in *International Bhurban Conference on Applied Sciences & Technology (IBCAST)*, 2014, pp. 1-4.

[6] S. K. Vavilala, V. Thirumavalavan, R. Thota, and S. Natarajan, Design of the fractional order internal model controller using the swarm intelligence techniques for the coupled tank system, *Turkish Journal of Electrical Engineering & Computer Sciences*, vol. 29, no. 2, pp. 1207-1225, 2021, doi: 10.3906/elk-2005-17.

[7] J. A. John, N. Jaffar, and R. M. Francis, Modelling and control of coupled tank liquid level system using backstepping method, *International Journal of Engineering Research & Technology*, vol. 4, no. 6, pp. 667-671, 2015.

[8] N. B. Almutairi and M. Zribi, Sliding mode control of coupled tanks, Mechatronics, vol. 16, no. 7, pp. 427-441, 2006, doi: 10.1016/j.mechatronics.2006.03.001.

[9] M. T. Alam, P. Charan, Q. Alam, and S. Purwar, Sliding Mode Control of Coupled Tanks System: Theory and an Application, *International Journal of Emerging Technology and Advanced Engineering*, vol. 3, no. 8, pp. 650-656, 2013.

[10] H. Abbas, S. Asghar, and S. Qamar, Sliding mode control for coupled-tank liquid level control system, 10th International Conference on *Frontiers of Information Technology*, 2012: IEEE, pp. 325-330.

[11] M. Saad, Performance analysis of a nonlinear coupled tank system using PI controller, *Universal Journal of control and automation*, vol. 5, no. 4, pp. 55-62, 2017.

[12] M. Saad, A. Albagul, and Y. Abueejela, Performance comparison between PI and MRAC for coupled-tank system, *Journal of Automation and Control Engineering*, Vol, vol. 2, no. 3, 2014, doi: 10.12720/joace.2.3.316-321.

[13] T. A. Folorunso, H. Bello-Salau, O. M. Olaniyi, and N. Abdulwahab, Control of a two-layered coupled tank: Application of IMC, IMC-PI and pole-placement PI controllers, 2013.

[14] P. G. G. Keerthana and J. Gnanasoundharam, Comparison of PI controller, model reference adaptive controller, and fuzzy logic controller for coupled tank system, *Indian Journal of Science and Technology*, vol. 9, no. 12, pp. 1-5, 2016.

[15] M. Dulău and T.-M. Dulău, Multivariable system with level control, *Procedia Technology*, vol. 22, pp. 614-622, 2016, doi: 10.1016/j.protcy.2016.01.128.

[16] T. L. Mien, Liquid Level Control of Coupled-Tank System Using Fuzzy-Pid Controller, *International Journal of Engineering Research & Technology (IJERT)*, vol. 6, no. 11, pp. 459-464, 2017.

[17] S. Sharma and M. Arora, Design and Comparison of PID & FUZZY Controller for

Water Level Control of Coupled Tank System.
[18] S. R. Mahapatro, B. Subudhi, and S. Ghosh, Design and real-time implementation of an adaptive fuzzy sliding mode controller for a coupled tank system, *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 32, no. 1, p. e2485, 2019, doi: https://doi.org/10.1002/jnm.2485.
[19] C.-T. Chao, N. Sutarna, J.-S. Chiou, and C.-J. Wang, An optimal fuzzy PID controller design based on conventional PID control and nonlinear factors, *Applied Sciences*, vol. 9, no. 6, p. 1224, 2019, doi: http://dx.doi.org/10.3390/app9061224.
[20] J. Nowakova and M. Pokorny, On PID controller design using knowledge-based fuzzy system, *Advances in Electrical and Electronic Engineering*, vol. 10, no. 1, pp. 18-27, 2012.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Mustafa Saad and Muad Alshara carried out the simulation and the optimization.
- Mustafa Saad and Muad Alshara have organized and executed the controller design and simulation of sections 3 and 4.
- Mustafa Saad and Khaled Mustafa were responsible for the text writing.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.