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Stabilization of liquid level in a tank system based on fuzzy logic controller

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ABSTRACT

Process industry needed a fast executed automatic control system capable of handling uncertain, vague problems and nonlinear control variables. Liquid level control is one of the emerging control problems getting the interest of technical experts in the area of control. This paper is based on a fuzzy logic control strategy to maintain and stabilize the liquid level in a tank system that deals with pumping of liquid in tanks as well as regulating liquid level and pushing off the liquid into another tank. Fuzzy controller attains optimum performance by eliminating perturbation in steady state and vanishing the overshoot as compared to proportional, integral, and derivative (PID) controller. The proposed fuzzy logic controller shows minimal steady error as compared to PID controller. The defuzzification of the proposed scheme is based on the centroid method to obtain optimum results. The settling time is nearly 50 second while using fuzzy logic control as compared to 80 seconds in PID control strategy. The overshoot observed is minimal, nearly less than 1% using a fuzzy logic control scheme.

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1. INTRODUCTION

In a coal drainage system due to nonlinear and uncertain variables it is extremely difficult to derive a mathematical model for a system which indicates law of motion as in traditional control systems because there are multiple variables involved interrelated to each other. The complexity of mathematical models creates challenges for control engineers in such cases. If the estimated model is not mapping to a real physical model, it leads to various perturbations subjected to controller and actuator degrading their performance [1], [2].

In the past decade, the control strategy based on the adaptive control problem of nonlinear systems got significant attention from the control engineering community while addressing the unmanned aerial vehicles (UAVs), robotic system and industrial control system as well. It was the major concern to attain better control performance through using sliding mode control, model predictive control and state feedback control [3]–[5]. The limitations of mentioned control techniques become dominant while addressing practical systems from real life that are based on complex nonlinear characteristics such as uncertain nonlinear dynamics, non-affine nonlinear dynamics. In various practical systems due to limitation of multiple factors and due to fluctuations in controller input the actuator may suffer and leads to failure [6].

To cater such situations the fuzzy logic controller is one of the emerging areas dealing with uncertain and vague problems. The only method is the fuzzy logic control system toward such a problem which transforms the linguistic variable defined by humans into fuzzy sets. In the mine drainage system, the fuzzy logic controller is superior to traditional automatic control[7]. Initiative about fuzzy logic got the attention of the scientific community in the early 90's. The Cleveland State University investigated the rule developing in fuzzy logic control. Fuzzy logic control systems gaining importance while solving vague and uncertain problems. As compared to modern control systems including sliding mode control, backstepping controller and proportional, integral, and derivative (PID) the fuzzy logic control does not depend on mathematical models but rely on membership function rules [8]. It is based on a pattern of logic which has an approximate mode of operation instead of exact values and competes with approximate data instead of classical data sets. Moreover, a fuzzy logic controller consists of a linguistic variable of daily life that deals with linear and nonlinear problems [9].

Ones can design a system with lower costs and superior features by attaining such attributes. In the last few decades fuzzy logic has attained technical significance in the industrial sector while solving multipurpose schemes [10]. Level control is one of the most dominating problems in industry dealing with process control. It reflects the wide range of attention of control engineers in nuclear power plants and in the cosmetic industry. Plant faces infrequent changes in level control due to different parametric changes, so maintaining the liquid near the desired point in liquid tanks is necessary [11]. A robust control can handle the disturbances occurring due to different parametric variations [12]. Different control algorithms have been applied to facilitate the liquid control system in chemical processes including a PID controller that deals with linear system problems with their limitation for nonlinear systems. Fuzzy logic control is efficiently used in nonlinear systems as well as for linear systems [13], [14].

Moreover, the major limitation of the traditional control algorithm is that it requires a precise mathematical model of the plant to control their dynamics. The mathematical model is a tedious job and sometimes it gets challenging to realize it for complex mechanical, electrical, and biological systems. However, the fuzzy control is based on fuzzy set theory and fuzzy logic, and it combines with traditional control strategy that stimulates the human thinking mode whose mathematical model is difficult to put together [15], [16]. The unknown nonlinear behavior can be approximated using fuzzy logic control. The chattering phenomena can be reduced more effectively using fuzzy logic controller as compared to PID controller [17].

The current research work focused on the implementation of fuzzy logic control for liquid tanks system and investigate the comparison of results obtained from linear control strategy for liquid control system in process control plant [18], [19]. The designed fuzzy logic controller only relies on membership functions instead of state equations that are essential to define the mathematical model of the physical system. The complete control phenomena are based on two steps including fuzzification and defuzzification while considering centroid methods. The achieved results are investigated in terms of transient response, steady state response, steady state error, rise time, settling as compared to linear control topology based on PID controller. The achieved results in terms of controller performance parameters including overshoot, settling time, steady state error and rise time etc. are superior PID controller for the proposed system being applied in process industries. The application of the proposed control strategy can be extended for application in home automations. The rest of the paper is organized as: Section 2 defines the state model of the liquid tank system, Section 3 is based on control strategy, and Section 4 discusses the simulation results and Section 5 comments on conclusion.

2. LIQUID TANK SYSTEM MODEL

Liquid level control was first introduced by Niimura [8] for small scale hydrogenating units based on fuzzy logic control. In a liquid tank system, the liquid enters a tank through orifices at top level and ejects from the orifice at the bottom level. The rate of flowing depends on the voltage applied to the pump and the rate of flowing out depends on the height of liquid in the tank. Figure 1 represents the schematic diagram of liquid tank system.

A differential equation for the height of liquid in the tank, H, is given as (1).

$$\dot{V} = A\dot{H} = bV - a\sqrt{H} \tag{1}$$

The first order differential (1) represents the liquid level in tanks. V is the volume of the liquid, and$H$ shows the height of the liquid in tanks which is the function of time rate of change. Similarly,$'a'$represents the flowing rate out of the tank and $'b'$ represents the flowing rate into the tank. It is a single input single output (SISO) nonlinear system. Using a Simulink control design tool for linearizing the nonlinearity and applied PID controller to regulate the level of liquid in the tank. The controller compares the desired level and actual level and alters the position of the valve as actuating signal or error varies. The differential (1) can be written as (2),

$$\dot{H} = bV/A - (a\sqrt{H})/A \tag{2}$$

which can also be written as (3),

$$\dot{x_1} = \frac{bu}{A} - \frac{a}{A} \times \sqrt{x_1} \quad (3)$$

where u is the input level, $'a'$ and $'b'$ are outlet and inlet flow rate, $x_1$shows the time rate of change of liquid level in the tank.

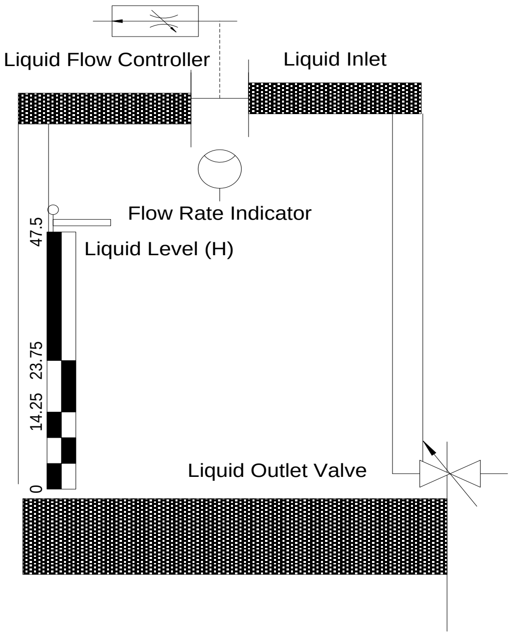

Figure 1. Liquid tank system model

3. CONTROL STRATEGY

The proposed control strategy is based on a fuzzy logic controller with fuzzy inference system (FIS) using Mamdani method for fuzzification of the input data which is the level and rate of flow of the liquid level in the tank. The basic "OR "operation is performed in Mamdani method with output variable which is to be controlled is liquid flow outlet valve. The membership function is defined representing the value of any variable between zero and one may be in fractions. The membership function used for input variable are level and rate of flow of the liquid in tank is Gaussian function having distinct feature of smooth transition of fractional value between zero and one can be mathematically expressed as (4).

$$f(x) = m \times e^{-(x-d)^2 / 2c^2} \quad (4)$$

In (4), the magnitude of Gaussian curve represented by $'m'$ and 'd' shows the position of the midpoint of the peak and $'c'$ shows the standard deviation. The membership function for the output variable $'H'$ is the function of is the flow rate at the outlet valve represents by triangular function in FIS editor because of its sharp transition between fractional value at output side. $f(x)$can be expressed as,

$$f(x;a,b,c) = \begin{Bmatrix} 0,\ x \leq a \\ \frac{x-a}{b-a},\ a \leq x \leq b \\ \frac{c-x}{c-b},\ b \leq x \leq c \\ 0,\ c \leq x \\ , \end{Bmatrix} \quad (5)$$

Fuzzy set characteristic of input level is given in Table 1. The level is varying from -1 to 1. The crisp range show the possible ranges for high, OK, and low level.

Table 1. Fuzzy set characteristic input level

Level	Range (-1 1) MF Used	Crisp Input Range
High	Gaussian	(0.5 -1)
OK	Gaussian	(0.5 0)
Low	Gaussian	(0.5 1)

Figure 2 shows the membership function plot of the input variable level for three different states including high, OK, and low using a Gaussian function as given in Table 1. The magnitude of the level is varying from 0-1. The three different ranges for level are high, OK, and low is shown in Figure 2 varying in Gaussian bell shaped curve. As the number of levels increases the membership function will also increase that will lead to more accurate tracking of the desired level. There is smooth transition in decaying each level from -1 to 1.

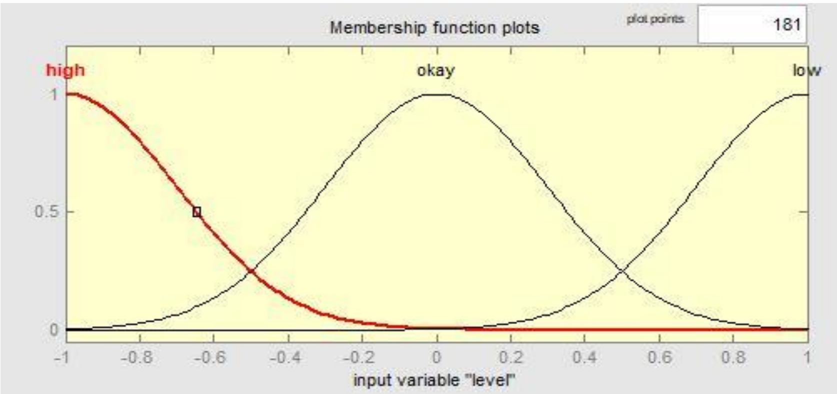

Figure 2. Fuzzy set membership function plot for input variable level

Table 2 shows the fuzzy set characteristic for the input variable flow rate. The flow rate is divided into three measures as shown in Figure 3 including negative, zero, positive. The range of the flow rate varies from 0.1 to -0.1. The flow rate is varying from negative to zero and then to positive. Figure 3 shows the fuzzy set membership function plot of input variable flow rate. The input flow rate to liquid level tank system is varying in Gaussian bell shaped curve. The variation in input flow rate in increasing exponentially and decaying exponentially without any rapid fluctuations.

Table 2. The fuzzy set characteristic input variable flow rate

Flow Rate	Range (-0.1 0. 1) , MF	Crisp input Range
Negative	Gaussian MF	(0.05 -0.1)
Zero	Gaussian MF	(0.05 0)
Positive	Gaussian MF	(0.05 0.1)

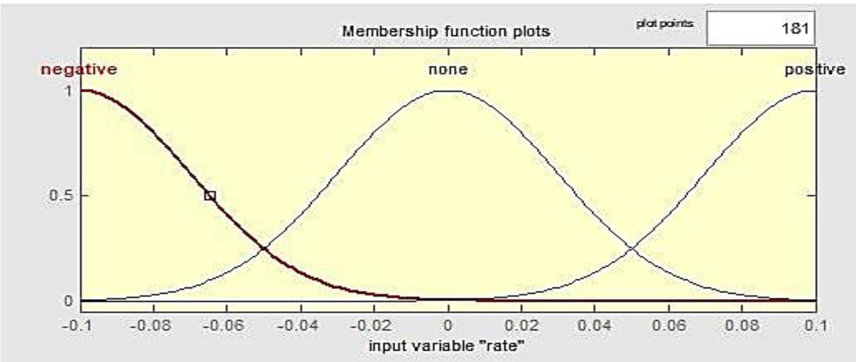

Figure 3. Fuzzy set membership function plot of input variable flow rate

The fuzzy set characteristic for the output variable which is the $'H'$ of the liquid in the tank depend on outlet flow rate at valve. The five possible states of the outlet valve are shown in Table 3. Figure 4 shows the membership function based on triangular function having five different states of the outlet valve including close fast, close slow, no changes, open fast and open slow. We can increase the number of states for the outlet valve in various fractions values. The triangular function shows the response of the opening position of valve is sharper as compared to input flow rate as in Gaussian curve. The numbers of memberships function for opening the valve are increased to respond more quickly to maintain the liquid level in the tank system. The magnitude of valve opening is varying from 0-1 as shown in Figure 4.

Table 3. Fuzzy set characteristic outlet valve

Valve states	Range(-1 1)	Crisp Input Range
Close_fast	Triangular MF used	(-1 -0.9 -0.6)
Close_slow	Triangular MF used	(-0.7 -0.5 -0.2)
No_change	Triangular MF used	(-0.3 0 0.3)
Open_slow	Triangular MF used	(0.1 0.3 0.6)
Open_fast	Triangular MF used	(0.5 0.7 1)

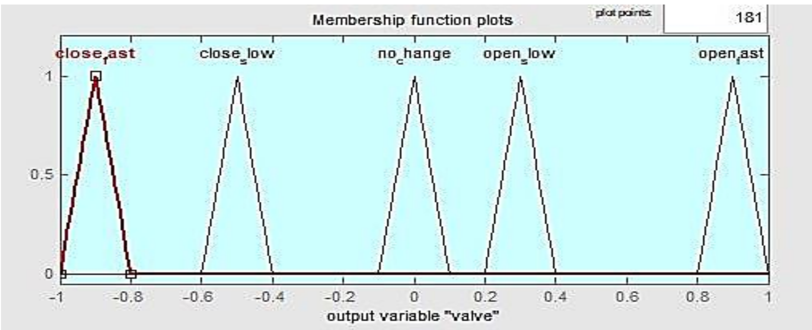

Figure 4. Fuzzy set characteristic of output variable valve

Figure 5 shows the rules editor window where rules can be added or changed. It shows the relation between input and output variable. In Figure 5 the rule first shows that if the level of the tank is OK then there is no need to change the value. Similarly, if the level is low then it directs to open the valve fast to attain the desired level required in the tank. The ruler editor allows you the option to construct the statements of the rules automatically by clicking one item in each input and output variable accordingly.

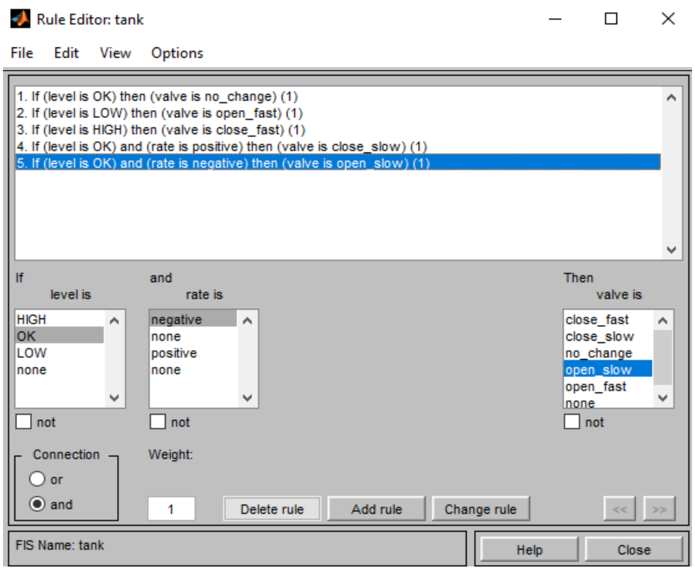

Figure 5. Membership rules of fuzzy set input and output variables of the liquid level tank system

Figure 6 shows the surface viewer of fuzzy set variables. It shows the relationship between all two input and single output variables graphically. The ranges for two inputs including the level and flow rate and output variable valve opening are shown in Figure 6. Figure 7 shows the complete visualization of the entire fuzzy FIS. It clarifies how the result is changed as the shape of the certain membership functions varies. The complexity of the system increases as the number of the input and output variables increases. As the number of the variables increases the rules may increase up to two to three times nearly with 30 rules for 6 to 7 variables as mentioned in [20]. The rules viewer presents you one variable at one time to identify the micro view of the fuzzy inference system identified in [21]. To visualize the entire output surface of your system it needs to stretch the output set on the complete span of the input set by opening the surface viewer window.

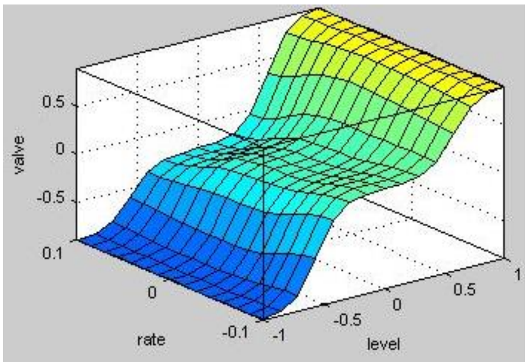

Figure 6. Surface view of fuzzy set input and output variables

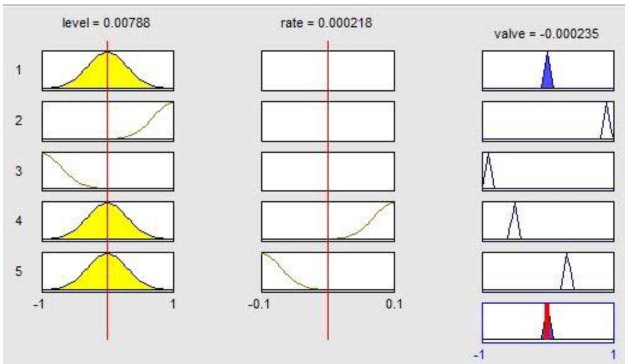

Figure 7. Rule Viewer of fuzzy set input and output variables

4. RESULTS AND DISCUSSION

Figure 8 shows the liquid level control of the tank system based on conventional PID controller as the desired level of the tank is 1. Initially the tracking error is maximum in transient state and slightly decreases in steady state. The overshoot is observed in the transient phase which is nearly 10%. The settling time is greater than 80 seconds. As time reaches to 30 seconds the steady state error is still significant that is nearly 12%.

Figure 9 shows the liquid level control of the tank system based on the fuzzy logic controller as the desired level of the tank is 1. It is evident from Figure 9 that fuzzy logic controller shows better performance in terms of overshoot, settling time and steady state error as compared to PID controller. The steady state error for fuzzy logic controller is nearly less than 1% which is quite lesser as compared to PID controller. The settling time for fuzzy logic controller is reduced to nearly 50 seconds from 80 seconds for PID controller as shown in Figure 9. The overshoot is also reduced to 5% for fuzzy logic controller of the liquid tank system.

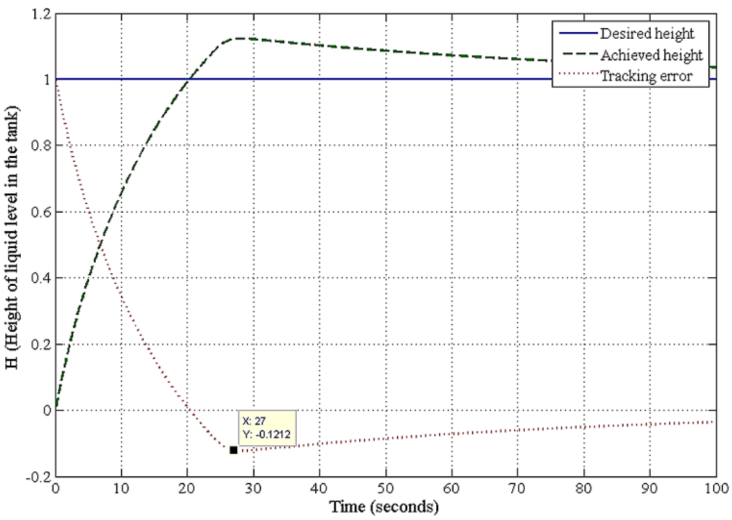

Figure 8. Liquid level control based on PID controller

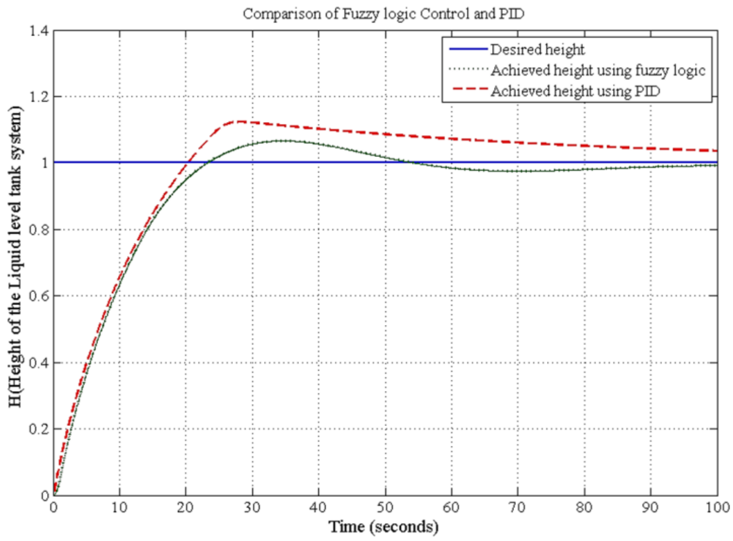

Figure 9. Comparison results of PID and fuzzy logic controller for liquid level tank system

Table 4 shows the comparison analysis of the PID controller strategy and fuzzy logic control system for liquid tank system. The superior features of the fuzzy logic controller for liquid tank system are shown the significance of fuzzy logic-based control system for practical system in various industries including chemical industries, processes industries, robotics, and manufacturing industries. The current research based on fuzzy logic control is strengthening its application for home automations, automation of various household appliances. The presented research work overcomes the limitation of linear control strategies like PID for various nonlinear systems in practical life.

Table 4. Performance comparison of PID controller and fuzzy logic controller

Performance attributes	PID Controller	Fuzzy logic controller
Overshoot	10%	5%
Settling time	>80 seconds	50 seconds
Steady state error	12%	<1%
Chattering	Not exist	Not exist

5. CONCLUSION

In the process control industry PID controller is prominently used to handle the linear problems with limitations for uncertainties and nonlinear control problems. Fuzzy logic controller is providing superior performance to cater to the nonlinear and vague problems. The result shown here provides significant improvement in maintaining transient and steady state response for nonlinear liquid level tank systems. The achieved result obtained for regulation of the liquid level in a tank system can be further extended to various industrial level controlling strategies including chemical manufacturing, biomedicine, and paints industry.

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REFERENCES

[1] Y. Xue, F. Gao, Y. Gao, X. Liang, Z. Zhang, and Y. Xing, "Thermo-hydro-mechanical coupled mathematical model for controlling the pre-mining coal seam gas extraction with slotted boreholes," *International Journal of Mining Science and Technology*, vol. 27, no. 3, pp. 473–479, May 2017, doi: 10.1016/j.ijmst.2017.03.012.

[2] K. Oraee and A. Goodarzi, "Mathematical modeling of coal seam methane drainage in longwall mining," in *SME Annual Meeting*, 2010, pp. 10–115.

[3] X. Cheng, Y. Zhang, H. Liu, D. Wollherr, and M. Buss, "Adaptive neural backstepping control for flexible-joint robot manipulator with bounded torque inputs," *Neurocomputing*, vol. 458, pp. 70–86, Oct. 2021, doi: 10.1016/j.neucom.2021.06.013.

[4] Z. Chen, X. Yang, and X. Liu, "RBFNN-based nonsingular fast terminal sliding mode control for robotic manipulators including actuator dynamics," *Neurocomputing*, vol. 362, pp. 72–82, Oct. 2019, doi: 10.1016/j.neucom.2019.06.083.
[5] A. Rauf, M. Zafran, A. Khan, and A. R. Tariq, "Finite-time nonsingular terminal sliding mode control of converter-driven DC motor system subject to unmatched disturbances," *International Transactions on Electrical Energy Systems*, vol. 31, no. 11, Nov. 2021, doi: 10.1002/2050-7038.13070.
[6] X. Deng and J. Wang, "Fuzzy-based adaptive dynamic surface control for a type of uncertain nonlinear system with unknown actuator faults," *Mathematics*, vol. 10, no. 10, May 2022, doi: 10.3390/math10101624.
[7] G. Wang and H. Song, "Study of the mine drainage fuzzy control system based on MATLAB," in *2009 International Conference on Intelligent Human-Machine Systems and Cybernetics*, 2009, pp. 99–102, doi: 10.1109/IHMSC.2009.33.
[8] A. S. Thakur, H. Singh, and S. Wadhwani, "Designing of fuzzy logic controller for liquid level controlling," *International Journal of u- and e-Service, Science and Technology*, vol. 8, no. 6, pp. 267–276, Jun. 2015, doi: 10.14257/ijunesst.2015.8.6.26.
[9] Q. Li, Y. Fang, J. Song, and J. Wang, "The application of fuzzy control in liquid level system," in *2010 International Conference on Measuring Technology and Mechatronics Automation*, Mar. 2010, pp. 776–778, doi: 10.1109/ICMTMA.2010.200.
[10] D. Wu and W. W. Tan, "A type-2 fuzzy logic controller for the liquid-level process," in *2004 IEEE International Conference on Fuzzy Systems (IEEE Cat. No.04CH37542)*, vol. 2, pp. 953–958, doi: 10.1109/FUZZY.2004.1375536.
[11] Q. Yongsheng, W. Yong, and S. Nan, "Design of liquid level control system of nuclear power plant," in *2013 IEEE 11th International Conference on Electronic Measurement & Instruments*, Aug. 2013, pp. 583–586, doi: 10.1109/ICEMI.2013.6743159.
[12] M. A. Sellitto, E. Balugani, R. Gamberini, and B. Rimini, "A fuzzy logic control application to the cement industry," *IFAC-PapersOnLine*, vol. 51, no. 11, pp. 1542–1547, 2018, doi: 10.1016/j.ifacol.2018.08.277.
[13] A. Ahmad, V. Redhu, and U. Gupta, "Liquid level control by using fuzzy logic controller," *International Journal of Advances in Engineering and Technology*, vol. 4, no. 1, 2012.
[14] T. K. Madhubala, M. Boopathy, J. S. Chandra, and T. K. Radhakrishnan, "Development and tuning of fuzzy controller for a conical level system," in *International Conference on Intelligent Sensing and Information Processing, 2004. Proceedings of*, 2004, pp. 450–455, doi: 10.1109/ICISIP.2004.1287699.
[15] H. F. VanLandingham and N. D. Tripathi, "Knowledge-based adaptive fuzzy control of drum level in a boiler system," in *Southcon/96 Conference Record*, 1996, pp. 454–459, doi: 10.1109/SOUTHC.1996.535109.
[16] C. Kanchana, T. Jayaweera, S. Jayasinghe, D. Jayawardana, and N. Wickramarachchi, "Intelligent water management system with remote access and monitoring," in *2013 1st International Conference on Artificial Intelligence, Modelling and Simulation*, Dec. 2013, pp. 23–28, doi: 10.1109/AIMS.2013.12.
[17] A. Rebai and K. Guesmi, "Robust adaptive fuzzy sliding mode controller for nonlinear uncertain hysteretic systems," *Transactions of the Institute of Measurement and Control*, vol. 42, no. 13, pp. 2519–2532, Sep. 2020, doi: 10.1177/0142331220921024.
[18] S. B. Prusty, U. C. Pati, and K. Mahapatra, "Implementation of fuzzy-PID controller to liquid level system using LabVIEW," in *Proceedings of The 2014 International Conference on Control, Instrumentation, Energy and Communication (CIEC)*, Jan. 2014, pp. 36–40, doi: 10.1109/CIEC.2014.6959045.
[19] D. E. Rivera, M. Morari, and S. Skogestad, "Internal model control: PID controller design," *Industrial and Engineering Chemistry Process Design and Development*, vol. 25, no. 1, pp. 252–265, Jan. 1986, doi: 10.1021/i200032a041.
[20] M. O. Okwu and A. N. Nwachukwu, "A review of fuzzy logic applications in petroleum exploration, production and distribution operations," *Journal of Petroleum Exploration and Production Technology*, vol. 9, no. 2, pp. 1555–1568, Jun. 2019, doi: 10.1007/s13202-018-0560-2.
[21] M. Dadwal and V. K. Banga, "Estimate ripeness level of fruits using RGB color space and fuzzy logic technique," *International Journal of Engineering and Advanced Technology*, vol. 2, no. 1, pp. 225–229, 2012.

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