



Control of Non-Linear Liquid Level Using Fuzzy logic System

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ABSTRACT

Level control systems play a crucial role across a wide range of industries, including oil and gas processing, nuclear power plants, and water treatment facilities. While Proportional-Integral-Derivative (PID) controllers are commonly used in these systems, its effectiveness could be limited by challenges such as nonlinearity, system uncertainty, and time delays.

To overcome these limitations, fuzzy logic control has appeared as a promising alternative. This paper investigates and compares the performance of traditional PID controllers with fuzzy logic controllers in handling non-linear level control systems.

MATLAB software and Simulink library were used to model and simulate the system in different control scenarios. The initial results indicate that fuzzy logic controllers outperform PID controllers by offering faster response times, minimal overshoot, and eliminating steady-state errors. Additionally, the system's response is evaluated under varying setpoint conditions to demonstrate adaptability.

التحكم في مستوى السائل غير الخطي باستخدام متحكم المنطق الضبابي

خلف الله عبد الله محمد حسين

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المُخلص

تُعد أنظمة التحكم في المستوى (Level Control Systems) من الأنظمة الأساسية المستخدمة في العديد من التطبيقات الصناعية، مثل صناعات النفط والغاز، والمحطات النووية، ومحطات معالجة المياه. وعلى الرغم من الانتشار الواسع للمتحكم التناسلي-التكاملي-التفاضلي (PID)، إلا أن أداءه قد يتأثر سلبًا عند التحكم في الأنظمة الغير خطية، تغير الباراميترز مع الزمن، وتأخيرات الزمن.

في هذا البحث، تم دراسة ومقارنة أداء متحكم PID التقليدي مع متحكم المنطق الضبابي (Fuzzy Logic Controller) في التحكم بأنظمة المستوى ذات السلوك اللاخطي. وقد تم استخدام برنامج MATLAB وبيئة Simulink لنمذجة النظام وإجراء المحاكاة تحت سيناريوهات تشغيل وتحكم مختلفة.

أظهرت النتائج الأولية أن متحكم المنطق الضبابي يحقق أداءً أفضل مقارنةً بمتحكم PID، حيث وفر زمن استجابة أسرع، وخفضًا ملحوظًا في نسبة التجاوز (Overshoot)، مع إزالة خطأ الحالة المستقرة (Steady-State Error). كما تم تقييم استجابة النظام عند تغيير قيم نقطة الضبط (Setpoint) لإظهار قدرة المتحكم الضبابي على التكيف مع ظروف التشغيل المختلفة، مما يؤكد كفاءته وفعاليته في التعامل مع الأنظمة غير الخطية.

الكلمات المفتاحية: التحكم في المستوى غير الخطي، متحكم PID، المنطق الضبابي، تتبع نقطة الضبط، المحاكاة باستخدام MATLAB/Simulink.

1 Introduction

Controlling liquid levels in industrial processes can be complex, especially when dealing with flowing substances such as chemicals. These processes require precise equipment to regulate the flow of liquid through inlet and outlet valves [1]. For this reason, it is essential that control system engineers have a solid understanding of liquid level dynamics and are prepared to address unpredictable changes.

Further research in the field of control systems is necessary to improve system response characteristics in term of overshoot, rise time, settling time, and steady-state error [2]. Traditional control systems were initially based on complex mathematical models, which are often difficult to implement in real-world applications.

To address these challenges, fuzzy control systems have emerged as a powerful alternative. Introduced by Professor Lotfi A. Zadeh in 1956, fuzzy logic controllers (FLCs) offer an intelligent control method that

transforms expert linguistic strategies into automatic control actions. Implementing fuzzy logic in industrial applications can enhance process performance, eliminate steady-state errors, and significantly improve overall system stability.

2 Literature Review

Numerous studies have demonstrated the superior performance of Mamdani-type Fuzzy Controllers (FCs) compared to traditional PID controllers. For example, in [3],[4], an FLC designed for a liquid-level tank system provided enhanced stability and faster adaptation under time delays, conditions under which the PID controller became unstable. The (FCs) also resulted in lower overshoot and improved steady-state behavior.

In studies [5],[6], FLCs were implemented in conical tank systems and compared against conventional PID controllers. The FLCs exhibited reduced oscillations, lower peak overshoots, and improved settling times. Performance evaluation metrics such as the Integral of Absolute Error (IAE), Integral of Time-weighted Absolute Error (ITAE), Integral of Time-weighted Squared Error (ITSE), and Integral of Squared Error (ISE) confirmed the FLC’s superior performance.

Study [7] examined Fuzzy-PI and Fuzzy-PID controllers in a hopper tank system. When compared to Ziegler-Nichols and Cohen-Coon tuned PID controllers, the Fuzzy-PID controller delivered lower integral error values and demonstrated the most effective control performance in simulations.

The 3-rules and 5-rules FLCs are designed and simulated using MATLAB software in work [8]. The results appearance satisfactory performance of 5-rules system, which responding in fast manner with output deviation. The better results achieved by varying some parameters, initial conditions and improved Simulink designs; to explore the viability of FCs method.

In paper [9], the fuzzy logic technique proposed to regulate and stabilize the level in a tank system that deals with pumping of liquid in cascade tanks. The introduced control system shows improved of transient response characteristics compared to PID controller.

In study [10], the advanced Fuzzy logic controller is developed for controlling the non-linear liquid quantity of the cylindrical vessel system. The performances of the proposed and PID controllers are compared using LabVIEW software over different operating points.

Lastly, [11] presented a synthesis algorithm to design a fuzzy-PD controller for controlling liquid level system.

The rate of level changing taken into account in the fuzzy controller of 5 rules. The steady state time was less than 10 seconds.

3 The configuration of PID Controller

PID controllers are typically recommended for use in slow processes—such as temperature control loops—that involve multiple time constants or significant dead time and are generally free from noise. In contrast, fast processes, which have short time constants, are more sensitive to process noise. Examples of such fast processes include flow control loops and liquid pressure control loops [12],[13].

The transfer function of a PID controller is given by:

$$G_C(s) = \frac{M(s)}{E(s)} = K_C \left(1 + \frac{1}{\tau_I s} + \tau_D s \right) \#(1)$$

Are a point to $M(s)$ = controller output variable, $E(s)$ = error signal, K_C = proportional gain, τ_I = integral (or reset) time and τ_D derivative (or rate) time.

Root locus is one of many methods used to tuning a PID controller. Depending on the designing characteristics (overshoot less than 10%, rising time =5 sec. and settling time=10 sec.), as in Fig. 1, the dominant poles will located at $-3.04 - j4.05$, with an associated gain of 2.31. So, the PID controller parameters are determined as $K_p= 8.061$, $K_i = 0.08$, and $K_D=2.31$.

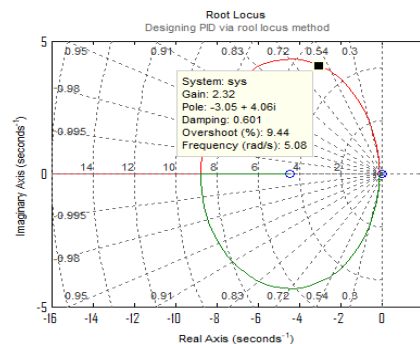


Fig 1: root locus sketch to design PID controller.

4 Fuzzy Logic Control System

Fuzzy logic is based on fuzzy set theory, which extends classical set theory by allowing partial membership of elements. A fuzzy set (A) in the universe of discourse (U) is characterized by a membership function $\mu_A(u)$, where each element u in U is assigned a membership value in the range [0,1] [14], [15].

$$A = (u, \mu_A(u)), u \in U \#(2)$$

The Mamdani rule is commonly employed for capturing expert knowledge. This allows us to utilize our expertise in a more intuitive, human-like manner. However, Mamdani-type FIS still entails a substantial computational burden [16],[17].

Fuzzy sets effectively handle uncertainty and imprecise information by allowing gradual transitions between membership and non-membership. Their overlapping nature provides interpolation capabilities, enabling smooth control actions. In fuzzy control systems, variables such as error (e), change in error (Δe), and change in control signal (Δu) are commonly represented as linguistic variables. These variables are linked through a rule base that covers the operating range of the process, typically using IF-THEN statements, e.g., “IF (e) is PB AND (Δe) is PS, THEN the valve opens rapidly” [18].

The structure of the fuzzy logic control (FLC) system is shown in Fig. 2. There are four main building blocks of the fuzzy logic controller: the fuzzification interface, fuzzy control rules base, inference engine and the defuzzification interface [19],[20].

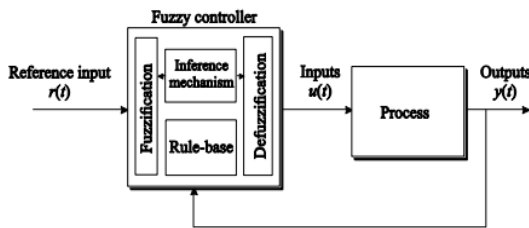


Fig 2: fuzzy controller system

5 Modelling of Level Control System

The open single-tank system shown in Fig. 3 can be modeled using the mass balance principle, which describes the relationship between the liquid level $H(t)$ and the inlet flow rate $Q_{in}(t)$ [21], [22].

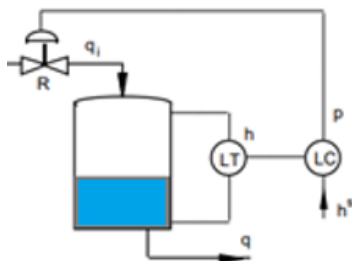


Fig 3: single tank water level system.

$$A \frac{dH(t)}{dt} = Q_{in} - Q_{out} \#(3)$$

According to Bernoulli’s equation

$$Q_{out} = a\sqrt{2gH(t)} \#(4)$$

$$A \frac{dH(t)}{dt} = Q_{in} - a\sqrt{2gH(t)} \#(5)$$

Where: a (outlet area of the tank= 0.012 m^2), A (cross-sectional area of the tank= 0.4 m^2), $g = 9.81 \frac{\text{m}}{\text{s}^2}$.

Fig. 4 shows the above calculations in block diagram form.

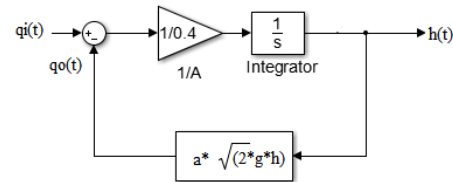


Fig 4: the block diagram of an open single tank level with an inflow and outflow.

The block diagram of Subsystem valve is represented in Fig. 5.



Fig 5: block diagram of a subsystem valve.

6 Designing of Fuzzy Logic System

The design of the fuzzy logic control system in Fig. 6 can be tested by using MATLAB/Simulink software.

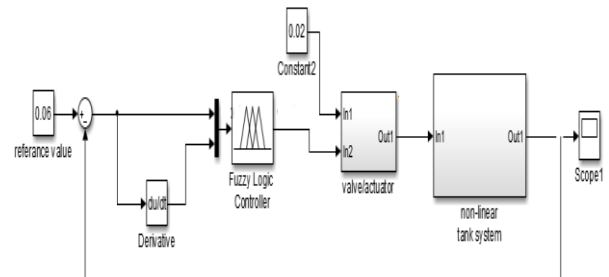


Fig 6: Simulink block diagram of control system.

Fig. 7.a and 7.b shows the fuzzification of two input variables which are error (e) [-0.05 , 0.05] with negative , zero and positive sets and delta of error (Δe) [-0.001 , 0.001]with negative (N),zero(Z) and positive(P) sets.

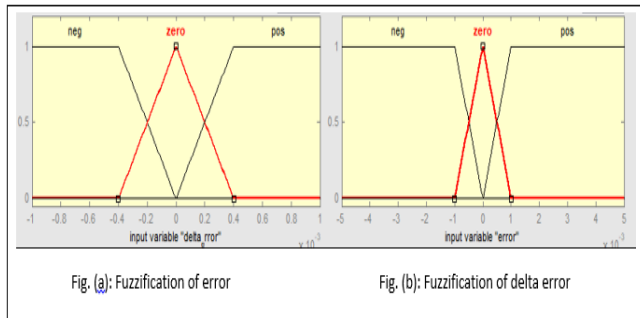


Fig 7: error and delta error as inputs of fuzzy control system.

The fuzzy controller output signal to the valve has three membership functions, Fig. 8: close fast, close slowly and no change.

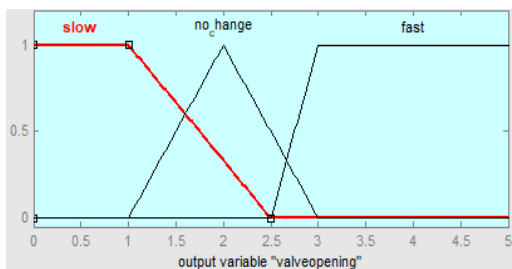


Fig 8: valve control signal as output of fuzzy logic system.

After fuzzification, the nine rules are used to make up the rule base shown in Fig. 9.

1. If (error is neg) and (delta_error is zero) then (valveopening is no_chang)
2. If (error is neg) and (delta_error is pos) then (valveopening is fast)
3. If (error is zero) and (delta_error is neg) then (valveopening is slow)
4. If (error is zero) and (delta_error is pos) then (valveopening is fast)
5. If (error is pos) and (delta_error is neg) then (valveopening is slow)
6. If (error is pos) and (delta_error is pos) then (valveopening is fast)
7. If (error is zero) and (delta_error is zero) then (valveopening is no_chang)
8. If (error is zero) and (delta_error is neg) then (valveopening is slow)
9. If (error is zero) and (delta_error is pos) then (valveopening is fast)

Fig 9: rule base considered.

7 Results and Discussion

Single input-single output fuzzy systems are simulated with error signal as input controller and valve opening single as output controller, as in Fig. 10, the rising time equal to 10 seconds and settling time was 20 seconds with 10% as steady state error and 0% overshoot.

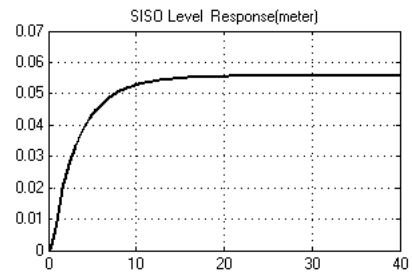


Fig 10: SISO fuzzy controller response.

The response of multi-inputs to fuzzy controller is shown in Fig. 11. The input variables error and Δ error, and valve control signal as output of FLC. The rise time is less than 10 seconds, 20 seconds as settling time and 0% overshoot and steady state error.

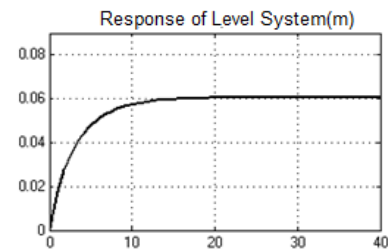


Fig 11: output response of fuzzy controller of two inputs.

Fig. 12 show how the error signal decreasing with increasing opening valve.

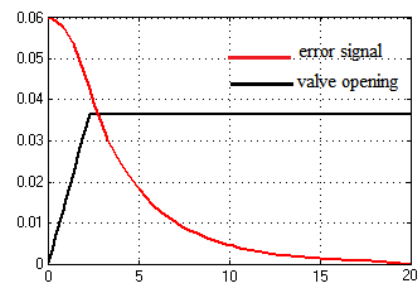


Fig 12: error signal decaying with opening actuator valve.

Fig. 13 illustrates the comparison between PID and fuzzy logic output response, which appears preference to the fuzzy control system than PID controller.

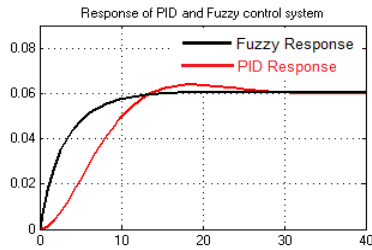


Fig 13: PID and Fuzzy controller response.

Fig. 14 illustrates the effectiveness of the fuzzy logic controller in accurately following dynamic setpoint changes, showcasing its robustness and adaptability in real-time, nonlinear control environments.

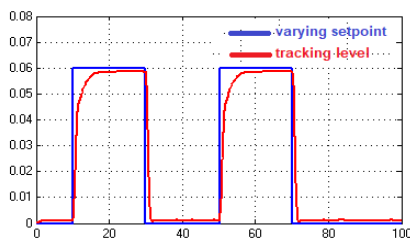


Fig 14: response of fuzzy logic with varying set point

The surface viewer in Fig. 15 illustrates how the fuzzy logic system maps the input variables to the corresponding control output. The smoothness of the surface indicates the continuous and nonlinear nature of the fuzzy control action, ensuring a gradual adjustment of the control signal

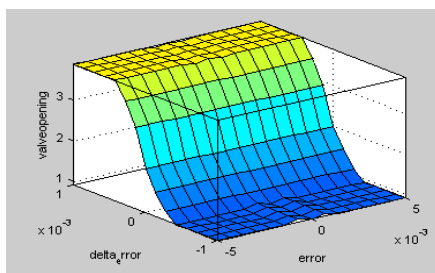


Fig 15: surface viewer of fuzzy control system.

8 Conclusions

The models of the non-linear level control systems are evaluated within the MATLAB-SIMULINK framework. Initially, traditional controllers are evaluated and are followed by the implementation of a Mamdani-type fuzzy logic system. The result shows significant improvement in performance over the widely

used PID design method in terms of rising time, steady state products and settling time. As seen in Fig. 13, In the case of fuzzy logic controller, the response was with zero percentage overshoot, the rise time decreasing by 25% and settling time lower by 50% than PID controller was. The FLC also with multi-input exhibits robust performance for plants with significant variation in dynamics and nonlinearities. When the set point varies with time, the fuzzy logic controller can track the set point changing. This method tries to recognise how the system input-output variables are influenced depending on the experiences rather than trying to model the system mathematically. This leads to simple, quicker and low-cost solutions.

Conflict of interest: The authors declare that there are no conflicts of interest

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