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Fuzzy Backstepping Control of Industrial Liquid Level System

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ABSTRACT

This paper presents a fuzzy backstepping controller design to improve the control performance of GUNT RT 512 industrial liquid level system. This system performs the process of reaching the liquid in the level tank to the level reference entered by the controller on it. The original control algorithm run on the ontroller is PID. In this study, the system is tested with a classical backstepping controller and fuzzy backstepping controller. The fuzzy logic controller determines one of the most important parameters of the backstepping controller. Constant and variable liquid levels are applied to the liquid level controller system. The system's dynamic responses are evaluated on response time, settling time, overshoot, and especially steady-state error. The parameter most in need of improvement is the steady-state error for the classical backstepping controller as this controller typically offers asymptotic tracking. Furthermore, the fuzzy backstepping proposes the exact tracking. The simulation results show that improvement has been achieved in almost all performance parameters with the proposed controller.

Endüstriyel Sıvı Seviye Sisteminin Bulanık Geri Adımlı Kontrolü

ÖZ

Bu makale, GUNT RT 512 endüstriyel sıvı seviye sisteminin denetim performansını iyileştirmek için, bir bulanık geri adımlamalı kontrolör tasarımı sunmaktadır. Bu sistem, seviye tankındaki sıvının, girilen s eviye referansına ulaşması işlemini denetleyici ile gerçekleştirmektedir. Denetleyici üzerinde çalıştırılan orijinal denetim algoritması PID'dir. Bu çalışmada sistem klasik geri adımlamalı denetleyici ve bulanık geri adımlamalı denetleyici ile test edilmiştir. Bulanık mantık denetleyici, geri adımlamalı denetleyicinin en önemli parametrelerinden birini belirlemektedir. Sıvı seviye denetim sistemine sabit ve değişken sıvı seviyeleri uygulanmıştır. Sistemin dinamik tepkileri tepki süresi, yerleşme süresi, aşım ve özellikle kararlı durum hatası açısından değerlendirilmiştir. İyileştirmeye en çok ihtiyaç duyulan parametre, klasik geri adımlamalı denetleyici için kararlı durum hatasıdır. Çünkü bu denetleyici tipik olarak asimptotik izleme sunmaktadır. Tersine, bulanık geri adımlama tam izleme önermektedir. Simülasyon sonuçları, önerilen denetleyici ile neredeyse tüm performans parametrelerinde iyileşme sağlandığını göstermektedir.

Anahtar Kelimeler: geri adımlamalı kontrol, bulanık geri adımlama, sıvı seviyesi, süreç kontrolü, GUNT RT 512

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1. Introduction

Liquid level control is crucial for production continuity and quality in industrial processes. This control plays an important role in many different systems such as tanks, reactors, storage tanks, pipelines, and chemical processes. For instance, controlling the liquid level in oil storage tanks is critical to the efficiency and safety of refinery operations in the petroleum industry [1]. In the chemical industry, accurately controlling the liquid level in reactors has a direct impact on product quality and process efficiency. Controlling the liquid level in storage tanks is critical for maintaining product quality and the proper execution of processes in the food industry.

Industrial liquid level systems measure liquid level through sensors and generate the necessary control signals based on these measurements with a control algorithm. The control input is used to maintain the liquid level at the reference value or to monitor a specific reference level. This process ensures that the liquid level is continuously monitored and intervenes when necessary to maintain the desired level.

PID controllers are frequently used to control liquid level systems due to their reliability, simple structure, and easy parameter tuning [2-4]. However, these controllers with fixed parameters are often inadequate in eliminating system errors and are generally unsuitable for the control of nonlinear systems since they cannot adapt to changing conditions. Therefore, various control methods such as fuzzy control, backstepping control, adaptive control, and sliding mode control are used to deal with nonlinearity and parameter uncertainties in temperature, pressure, level, humidity, velocity, and flow.

The backstepping approach is used to control nonlinear systems through feedback. The determination of the control rule is based on the Lyapunov theorem [5]. The main advantage of using this method is the fast response to disturbances by taking into account the nonlinearity of the system. Especially in nonlinear systems such as liquid level control, the ability of the backstepping approach to react quickly to disturbances is an important advantage. Literature reviews support that this method can be quickly adapted to liquid level control systems and provide the desired performance. Recent studies show that the backstepping approach in liquid level control is increasing. Yang et al. [6] suggest a robust backstepping control method based on a finite-time disturbance observer for output tracking of a three-tank system in the presence of uncertainties. A finite-time virtual control is designed for the output tracking of the system along with a dynamic surface control technique. Theoretical analysis is performed on the whole system. Gomaa et al. [7] proposed a command-filtered backstepping control method for liquid level monitoring in a nonlinear coupled three-tank system. The standard backstepping controller was tested experimentally and found that the control signal fluctuates rapidly between two thresholds, which would damage the pump. The obtained results confirm the effectiveness and practical use of the proposed approach. Meng et al. [8] present an integral backstepping control approach based on a disturbance observer for a two-tank liquid level system under external disturbances. The simulation and experimental findings validate that the integral backstepping control methodology based on disturbance observer exhibits favorable dynamic and static performance compared to the disturbance observer-based sliding mode control approach. Meng et al. [9] extended a compound control method and implemented a novel disturbance observer-based feedback linearization control strategy for a four-tank liquid level system. The simulation and experimental studies, as well as comparisons between the PID control of the system and the proposed control strategy, show that it offers significant advantages including minor control errors and robust disturbance suppression capabilities. Table 1 shows the summary of key findings for the literature.

The main objective of the liquid level controller is to reach the reference level quickly, accurately, and stable. This can be ensured with robust control algorithms. Among them, the backstepping controller, which is based on the Lyapunov Theorem, guarantees stability. However, it does not guarantee the exact desired level. So, there is mostly steady state error with the classical backstepping controller. To overcome this, fuzzy logic control is used and the system response is improved.

In this study, modeling of the liquid level control using the fuzzy backstepping method is carried out. The backstepping control method offers an effective control strategy with repeated backward steps to reach the reference value. Nevertheless, the classical backstepping method enables asymptotic tracking. Upon reaching the target state, the system typically stabilizes at a position that is close to the target but not precisely at the target. This results in a continuous steady-state error. To solve this problem, fuzzy logic controller is used in this study.

Table 1. Key findings of existing research

Name	System	Approach	Results
Robust nonlinear control of a three-tank system using finite-time disturbance observers [6]	Inteco three-tank system	Finite-time disturbance observer-based robust control method by using backstepping design	The system exhibits input-to-state practical stability (ISpS), ensuring that the total error remains bounded despite the presence of uncertainties. These uncertainties no longer significantly influence the system's long-term behavior."
Command-Filtered Backstepping Control of Multitank System [7]	Inteco three-tank system	Command-Filtered Backstepping Control	Demonstrates robust tracking performance for liquid level and control signal
Disturbance Observer-Based Integral Backstepping Control for a Two-Tank Liquid Level System Subject to External Disturbances [8]	Liquid level system with two tanks of four-tank NTC-I type.	Disturbance observer-based integral backstepping control	The disturbance observer-based integral backstepping control methodology exhibits superior dynamic and static performance compared to the disturbance observer-based sliding mode control approach. The proposed controller demonstrates significantly improved steady-state and transient response characteristics relative to various complex algorithms.
Disturbance Observer-Based Feedback Linearization Control for a Quadruple-Tank Liquid Level System [9]	Quadruple-tank liquid level (QTLL) system	Input/output feedback linearization control method by utilizing nonlinear disturbance observer	The proposed control scheme demonstrates superior performance relative to PID control and disturbance observer-based sliding mode control (DO-SMC). This advantage manifests in reduced control error and enhanced disturbance rejection capabilities.
This study	GUNT RT 512 single tank liquid level system	Fuzzy backstepping control	The proposed controller overcomes the steady state error exactly. The control performance gets better with the fuzzy approach.

Fuzzy logic controllers are used to address the uncertainties inherent in the system, to improve the decision algorithm, and to control nonlinearities more adaptively. In this study, a fuzzy backstepping control algorithm is established by adjusting the backstepping stability constant. The fuzzy backstepping algorithm provides robust control by managing the uncertainties and variations of the system. Classical backstepping control and fuzzy backstepping control algorithms are implemented for the liquid level system to compare the control performance. The performance criteria for the controllers are the desired characteristics for the transient and steady-state terms of the dynamic response, which are steady-state error (e_{ss}), rise time (t_r), peak time (t_p), settling time (t_s), and percentage overshoot (M_p%). The results show that the fuzzy backstepping approach has improved the control performance. The designed controllers are tested for increasing-decreasing trajectories with fixed reference values. As a result, it is shown that fuzzy backstepping control provides more effective control than classical backstepping control.

The organization of this paper is as follows: Section 2 covers the technical specifications of the controlled system, its mathematical model, the backstepping control algorithm, and fuzzy logic control. Section 3 details the design of the fuzzy backstepping controller. Section 4 presents the simulation results for specific level data. Finally, section 5 presents the conclusions drawn.

2. System Description and Problem Statement

2.1. System description

The GUNT RT 512 liquid level controller has a similar operation to the process controllers commonly used in industry. The block diagram including the components of the system is shown in Figure 1. The main purpose of the system is to arrange the liquid in the level tube to the specified value. For this purpose, the pressure information of the liquid is sensed and converted into current information with the pressure/current sensor and compared with the reference level information by the controller. Accordingly, the current information to be transmitted to the pneumatic control valve is determined by the controller. The liquid in the system circulates in a continuous loop, as the liquid pump continuously delivers liquid to the level tube and the outlet valve continuously discharges liquid. The controller adjusts the current information controlling the pneumatic control valve to achieve the desired liquid level.

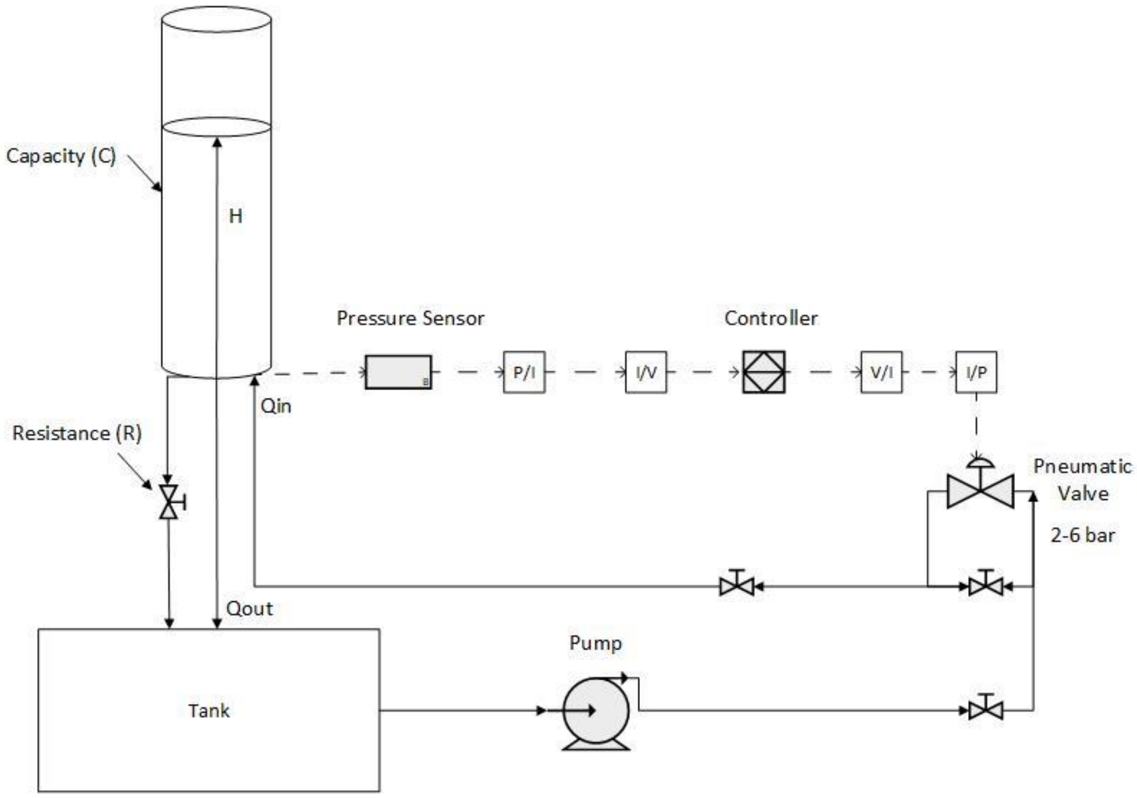


Figure 1. System components of the liquid level controller, GUNT RT 512.

Since there is a pipe valve at the outlet of the GUNT RT 512 liquid level system, resistance occurs in the system. This resistance R is expressed by change in liquid height in the system H with liquid flow out of the liquid level tank Q_{out} . The resistance of the system is found in Equation 1.

$$R = \frac{Change\ in\ liquid\ height\ (mm)}{Fluid\ flow\ to\ the\ outside\ (mm^3/sn)} = \frac{H}{\text{Qout}} \tag{1}$$

The ratio of the change in liquid volume to the change in liquid height is the capacity of the level tank, C, and is expressed by Equation 2.

$$C = \frac{Change\ in\ liquid\ volume\ (mm^3)}{Change\ in\ liquid\ height\ (mm)} = \frac{dV}{dH} \tag{2}$$

In this case, the level tank is thought to be linear, the difference between the flow of water entering the level tank and the flow leaving the level tank is expressed in Equation 3, taking into account the capacity.

$$C\frac{dH}{dt} = Q_{in} - Q_{out} \tag{3}$$

Using Equation 1 and Equation 3, Equation 4 is obtained.

$$RC\frac{dH}{dt} + H = RQ_{in} \tag{4}$$

Equation after taking the Laplace transform of Equation 4, Equation 5 is obtained.

$$G_t(s) = \frac{H(s)}{Q_{in}(s)} = \frac{R}{RAs+1} \tag{5}$$

Fluid resistance to obtain a mathematical model of the system R and capacitance C values should be calculated. Ergüzel calculated these values as R=0.012 and A=10032 in his study [5]. In this case, the Transfer Function is obtained as Equation 6.

$$G_t(s) = \frac{0.012}{(0.012*10032)s+1} = \frac{0.012}{120.38*s+1} \quad (6)$$

The amount of liquid sent to the liquid level tube depends on the opening of the pneumatic valve. The pneumatic valve used in the system is controlled by current. With the 4-20 mA current supplied to the pneumatic valve, the valve operates and the liquid is transferred to the liquid level tube via Q_in, which is the liquid flow at the valve outlet. The gain of the pneumatic valve is calculated as Kv =14000 in the case indicated by [10]. In this case, the Transfer Function of the process is obtained in Equation 7.

$$G_p(s) = K_v(s) * G_t(s) = 14000 * \frac{0.012}{(0.012*10032)s+1} = \frac{168}{120.38*s+1} \quad (7)$$

2.2. Backstepping control

Backstepping is a control strategy used in the control of dynamic systems. This strategy is often effective in controlling systems with nonlinearities and uncertainties. Stabilizing the system's states in the direction of the origin, which is thought to be the equilibrium point is the control objective. Backstepping control's fundamental concept is to decompose a complex nonlinear system into smaller subsystems that don't go beyond the system's order, and then create a virtual control element based on Lyapunov functions for each smaller subsystem [11].

Backstepping control defines control surfaces and designs control laws for these surfaces to guide the system to the desired target. In backstepping control, there is a control signal, called virtual control, which is not applied on the real system but is calculated as a part of the backstepping algorithm. The virtual control is used to determine the control surfaces in the backstepping steps performed and to steer the system towards the desired behavior. Self-iteration is important in determining the success of the backstepping control algorithm and how fast the system reaches the desired goal. A Lyapunov function is formulated to encompass the entirety of the system, incorporating parameter estimations. The Lyapunov function is used to analyze the stability of the backstepping control algorithm. As an example, the mathematical model of the backstepping control algorithm of a third-order system is considered.

$$\dot{x}_1 = x_2 + x_1^2$$
$$\dot{x}_2 = x_3 + x_2^2$$
$$\dot{x}_3 = u \quad (8)$$

The state variables are x_1, x_2, and x_3. The control input is u. Designing a state feedback control for asymptotically stabilizing the origin is the control's goal.

1. The first state variable is $x_1 = z_1$ and the derivative of this state variable is expressed in Equation 9.

$$\dot{x}_1 = \dot{z}_1 = x_2 + x_1^2 \quad (9)$$

x_2 is considered to be a real control variable. Additionally, a virtual control law is described for Equation 9 and a variable,$\alpha_1$is defined. z_2 is the error that is the difference between the real and virtual control variables. It is given in Equation 10.

$$z_2 = x_2 - \alpha_1 \quad (10)$$

Equation 9 is rewritten in Equation 11.

$$\dot{z}_1 = \alpha_1 + x_1^2 + z_2 \quad (11)$$

The goal is to design a virtual control law α_1 while $z_1 \to 0$. At this stage, the first Lyapunov candidate function is defined as in Equation 12.

$$V_1 = \frac{1}{2}z_1^2 \quad (12)$$

The derivative of the Lyapunov function is calculated in Equation 13.

$$\dot{V}_1 = z_1(\alpha, +x_1^2) + z_1 z_2 \quad (13)$$

A suitable virtual control α_1 is selected to stabilize the first-order system.

$$\alpha_1 = -C_1 z_1 - x_1^2 \quad (14)$$

$$\dot{\alpha}_1 = -(C_1 + 2x_1)(x_2 + x_1^2) \quad (15)$$

The derivative of V_1 is rewritten with positive C_1 in Equation 16.

$$\dot{V}_1 = -C_1 z_1^2 + z_1 z_2 \quad (16)$$

If z_2 is 0, in other words, the real control variable equals the virtual control, then $\dot{V}_1 = -C_1 z_1^2$ and a symptotic convergence of z_1 to zero is assured.

2. The derivative of the error, z_2, and a virtual control law is expressed in Equation 17.

$$\begin{aligned}\dot{z}_2 &= \dot{x}_2 - \dot{\alpha}_1 \\ &= x_3 + x_2^2 + (C_1 + 2x_1)(x_2 + x_1^2)\end{aligned} \quad (17)$$

α_2 is selected as a virtual control law. A virtual control input, x_3, is identified. z_3 is calculated as an error to define the difference between real and virtual controls.

$$z_3 = x_3 - \alpha_2 \quad (18)$$

Equation 17 is updated.

$$\dot{z}_2 = z_3 + \alpha_2 + x_2^2 + (C_1 + 2x_1)(x_2 + x_1^2) \quad (19)$$

The aim is to $z_2 \to 0$. Here, new Lyapunov function is defined.

$$V_2 = V_1 + \frac{1}{2}z_2^2 \quad (20)$$

The derivative of this function is expressed in Equation 21.

$$\begin{aligned}\dot{V}_2 &= \dot{V}_1 + z_2\dot{z}_2 \\ &= -C_1 z_1 + z_1 z_2 + z_2\big(z_3 + \alpha_2 + x_2^2 + (C_1 + 2x_1)(x_2 + x_1^2)\big) \\ &= -C_2 z_2^2 + z_2, \alpha_2 + z_1 + x_2^2 + (C_1 + 2x_1)(x_2 + x_1^2) + z_2 z_3\end{aligned} \quad (21)$$

A suitable virtual control α_2. is selected.

$$\alpha_2 = -z_1 - C_2 z_2 - x_2^2 - (C_1 + 2x_1)(x_2 + x_1^2) \quad (22)$$

$\dot{V}_2$ is recalculated.

$$\dot{V}_2 = -C_1 z_1^2 - C_2 z_2^2 + z_2 z_3 = -\sum_{i=1}^{2} C_i z_i^2 + z_2 z_3 \quad (23)$$

There is an asymptotic assurance that z_1 and z_2 converge to zero if $z_3 = 0$ and so $\dot{V}_2 = -\sum_{i=1}^{2} C_i z_i^2$.

3. The steps are repeated for the error, $z_3 = x_3 - \alpha_2$.

$$\dot{z}_3 = u - \frac{\partial\alpha_2}{\partial x_1}(x_2 + x_1^2) - \frac{\partial\alpha_2}{\partial x_2}(x_3 + x_2^2) \quad (24)$$

As mentioned above, $x_3 = u$ and so the real control input is u. The aim is designing the real control input u so that $z_1, z_2,$ and z_3 converge to zero. The selected Lyapunov candidate function V_3 is in

Equation 25.

$$V_3 = V_2 + \frac{1}{2} z_3^2 \tag{25}$$

The derivative is given in Equation 26.

$$\dot{V}_3 = -\sum_{i=1}^{2} C_i z_i^2 + z_3\left(u + z_2 - \frac{\partial \alpha_2}{\partial x_1}(x_2 + x_1^2) - \frac{\partial \alpha_2}{\partial x_2}(x_3 + x_2^2)\right) \tag{26}$$

The control input u is designed for $\dot{V}_3 \leq 0$.

$$u = -z_2 - C_3 z_3 + \frac{\partial \alpha_2}{\partial x_1}(x_2 + x_1^2) + \frac{\partial \alpha_2}{\partial x_2}(x_3 + x_2^2) \tag{27}$$

Derivative of the Lyapunov candidate function V_3 is taken.

$$\dot{V}_3 = -\sum_{i=1}^{3} c_i z_i^2 \tag{28}$$

2.3. Fuzzy Logic Control

A fuzzy logic controller, an effective tool for modeling and regulating complex systems, offers more adaptable and flexible solutions in real-world applications. This presents a problem-solving methodology within control systems, offering an algorithmic framework for converting expert-derived linguistic control strategies into automatic control strategies [12].

Fuzzy logic controllers are primarily based on fuzzy sets and fuzzy rules and effectively employ uncertainty and non-discrete concepts to comprehend and forecast the system's behavior, which enhances control performance and guarantees system stability.

An iterative control method, backstepping control, offers obvious advantages for control systems with mismatched uncertainty and is useful for nonlinear systems to handle disturbances and uncertainties [13]. However, in general, backstepping control algorithms are thought to be ineffective control strategies for fixing steady-state errors. This is because backstepping typically offers asymptotic tracking, meaning the system keeps going until it reaches the desired state. Nevertheless, upon reaching the target state, the system generally attains stabilization in proximity to the target rather than precisely at the target location. To overcome this and enhance the robustness and effectiveness while simultaneously improving the dynamic response of the systems, some methods have been developed. Backstepping control with an integral function is the most common method to lower the steady-state error [14]. The other method is to use a fuzzy logic controller [13].

In this study, the function of fuzzy logic in fuzzy backstepping control is to adjust the parameter of the corresponding backstepping controller, c_2 control gain, according to the state of the system. Thus, a stepback controller with variable control gain is obtained. The fuzzy logic controller has two inputs and one output. The relevant error z_1 and its derivative, $\dot{z}_1$, in other words, z_2, are taken as inputs and are given with Equation 29 and Equation 30. The control gain c_2 is the control input value for the liquid level control system. The block diagram of the fuzzy logic backstepping controller is given in Figure 2.

$$z_1 = h_{ref} - h_{out} \tag{29}$$

$$z_2 = \dot{z}_1 \tag{30}$$

h_{ref} is the reference liquid level value and h_{out} is the system liquid level output.

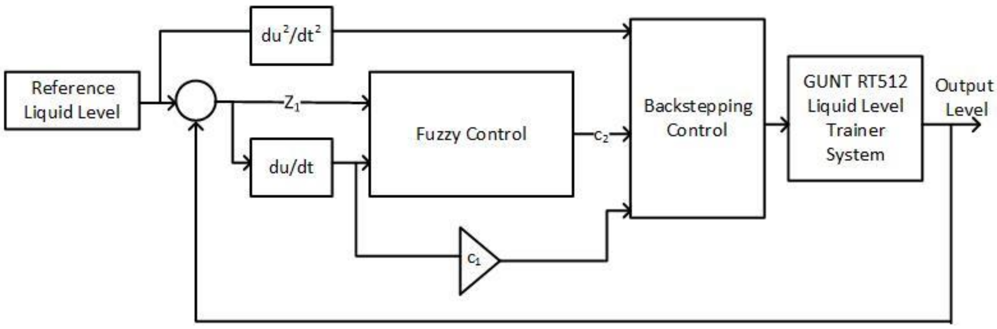
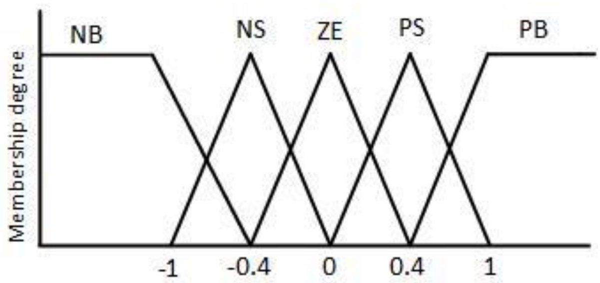


Figure 2: Block diagram of liquid level control system with fuzzy backstepping control

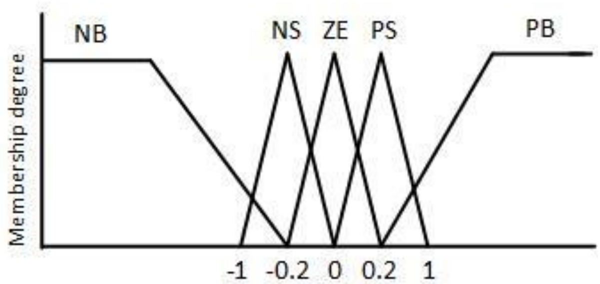
3.Fuzzy Backstepping Control Design

In regulating problems, the error variable is tried to be made zero. The controller and the dynamics of the system determine whether it drops or reaches zero. In this algorithm, the control gain c_2, which is effective in reducing the error term, is adjusted with fuzzy logic to make the error variable z_1 zero as fast as possible and thus improve the system performance. When the error, z_1 is large, the control gain value c_2 is chosen sufficiently large, and when the error z_1 is small, the control gain value c_2 is chosen small. Also, by evaluating the variable z_2 in addition to z_1, the control gain is changed according to the change trend of z_1.

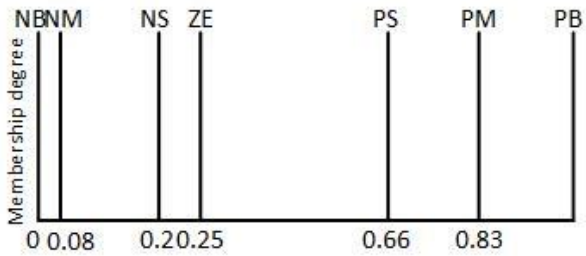
Figures 3 (a) and (b) show the inputs for the error z_1 and derivative of error z_2 using five triangular normalized membership functions (MFs), which are the most commonly employed in fuzzy logic control design. Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB) are the linguistic variables. Positive Medium (PM) and Negative Medium (NM) are the additive linguistic labels for the output MFs.



a) Fuzzy logic control input MFs for error, z_1



b) Fuzzy logic control input MFs for the derivative of error, z_2



c) Fuzzy logic control output singleton MFs for c_2 control gain

Figure 3. The MFs for the fuzzy backstepping controller

The rule base for the fuzzy logic control is given in Table 2. It is obtained from the Mac-Vicar Whelan rule base.

Table 2. Rule base for control gain c_2

z_1 / z_2	***NB***	***NS***	***ZE***	***PS***	***PB***
NB	NB	NB	NM	NS	ZE
NS	NB	NM	NS	ZE	PS
ZE	NS	NS	ZE	PS	PM
PS	ZE	ZE	ZE	PM	PB
PB	ZE	PS	PM	PM	PB

4. Results and Discussion

There are various criteria used to evaluate the performance of the dynamic systems. These criteria are important for determining the ability of the system to perform the desired behaviors. Response time and settling time determine how quickly the system reaches the desired state and settles to the desired values, while overshoot evaluates unwanted overreactions. These performance criteria play an important role in system design and control processes.
MATLAB/Simulink was used to simulate the liquid level controller in this study. A comparative analysis of the results obtained from a classical backstepping controller has been used to evaluate the performance of the suggested fuzzy backstepping controller. Various performance criteria have been observed as overshoot, rising time, and especially steady-state error.

Since the backstepping control is based directly on the principles of mathematical modeling and control theory, the system models should generally be linear and deterministic. However, in fuzzy backstepping control, according to the principles of fuzzy logic and control theory, system models can often contain uncertainty and do not require linearity assumptions. To verify the effectiveness of the controllers, the system model was created and the test was performed at different liquid levels and for changing levels.

Figure 4 shows both system responses for the constant reference liquid level, 25 cm. The level is described with a Constant Simulink block. The figure shows the continuous steady-state error with classical backstepping. This error problem is solved with the fuzzy backstepping controller.

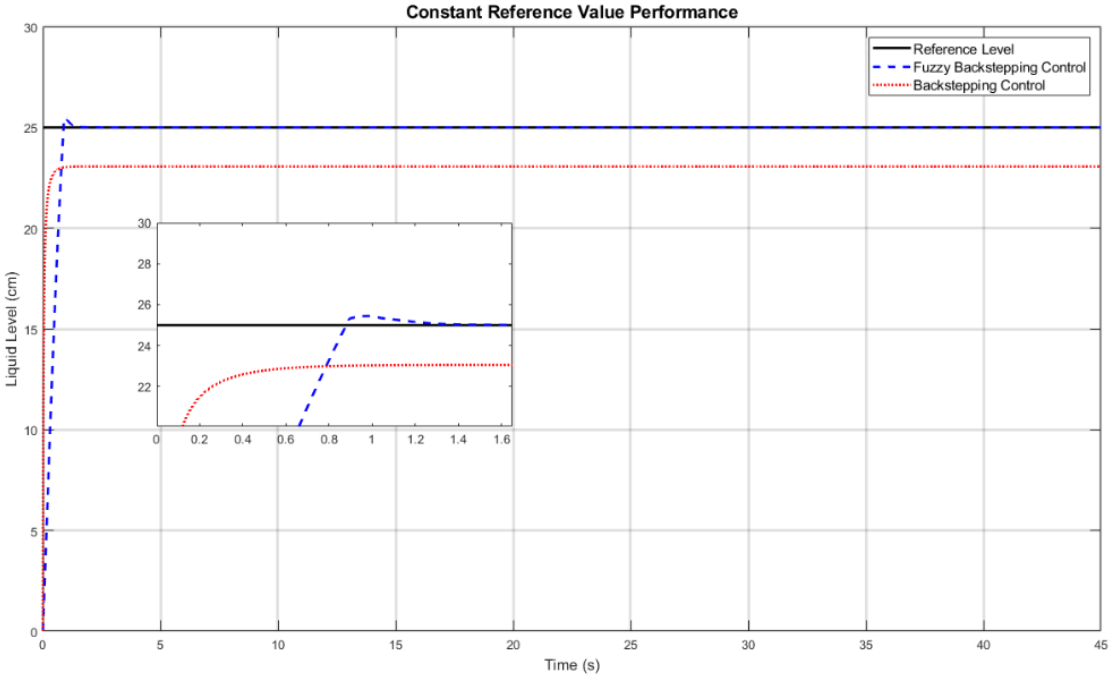


Figure 4. System responses for constant 25 cm liquid level

To test the system behavior for the rising reference levels, the reference liquid level was set to 30 cm for the first 15 seconds and the reference was changed to 45 cm on the 15th second. This situation is shown in Figure 5. The rising time for the classical and fuzzy backstepping controller is nearly the same and additionally, there is no overshoot and no steady state error with the fuzzy backstepping controller. The steady-state error is still a problem with the classical backstepping controller.

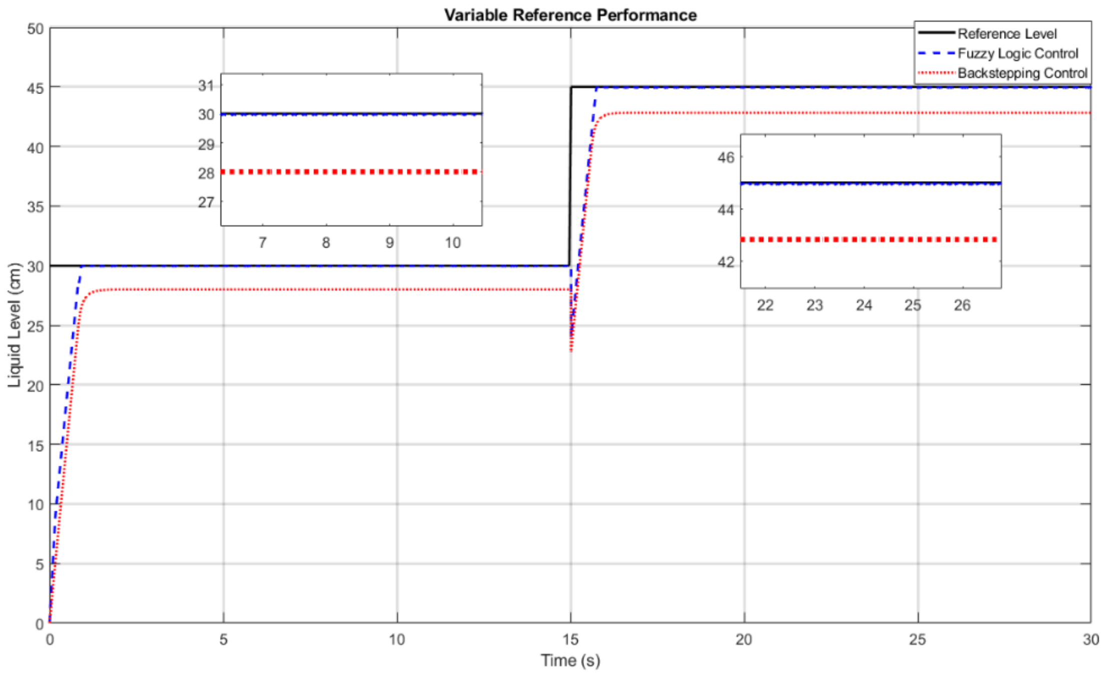


Figure 5. System responses for interval constant liquid level (increasing constant liquid level)

The test was repeated to decrease reference liquid levels. For the first 20 seconds, the reference was set to 45 cm, and for the rest simulation time, the reference was set to 30 cm. As seen in Figure 6, there is still a steady state error with the classical backstepping controller.

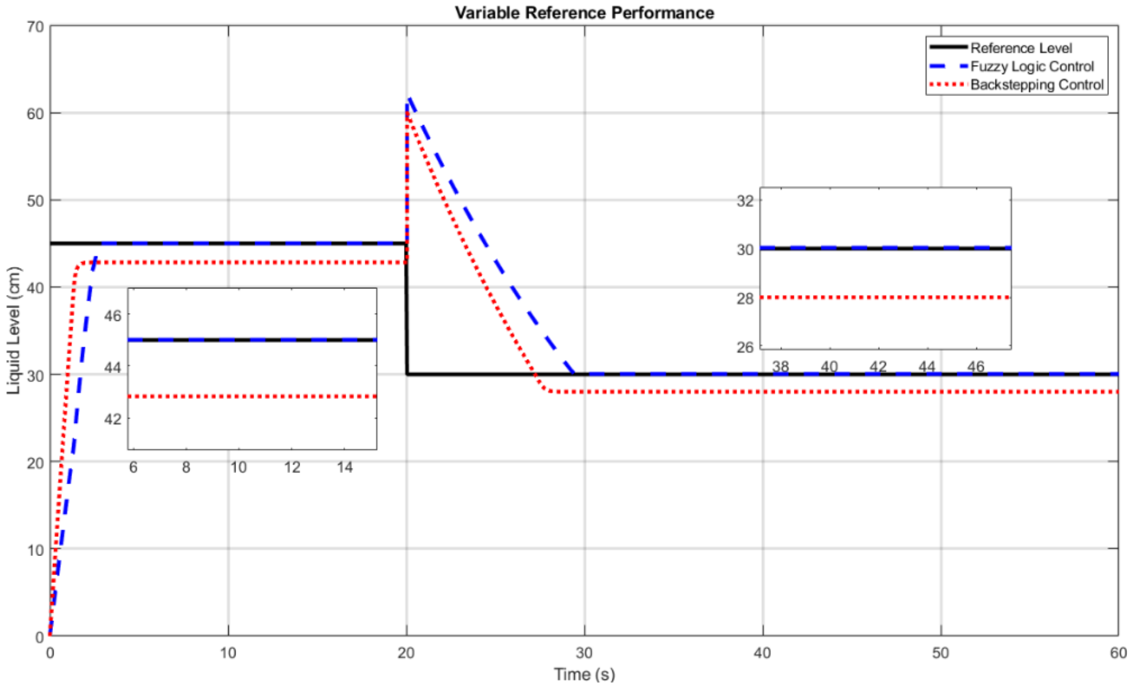


Figure 6. System responses for interval constant liquid level (decreasing constant liquid level)

To test the tracking performance of the controllers, the reference input is set to the time-variant level as seen in Figure 7. The response of the fuzzy backstepping controller is the same as the reference signal. However, the classical backstepping controller tracks the reference signal with a steady-state error.

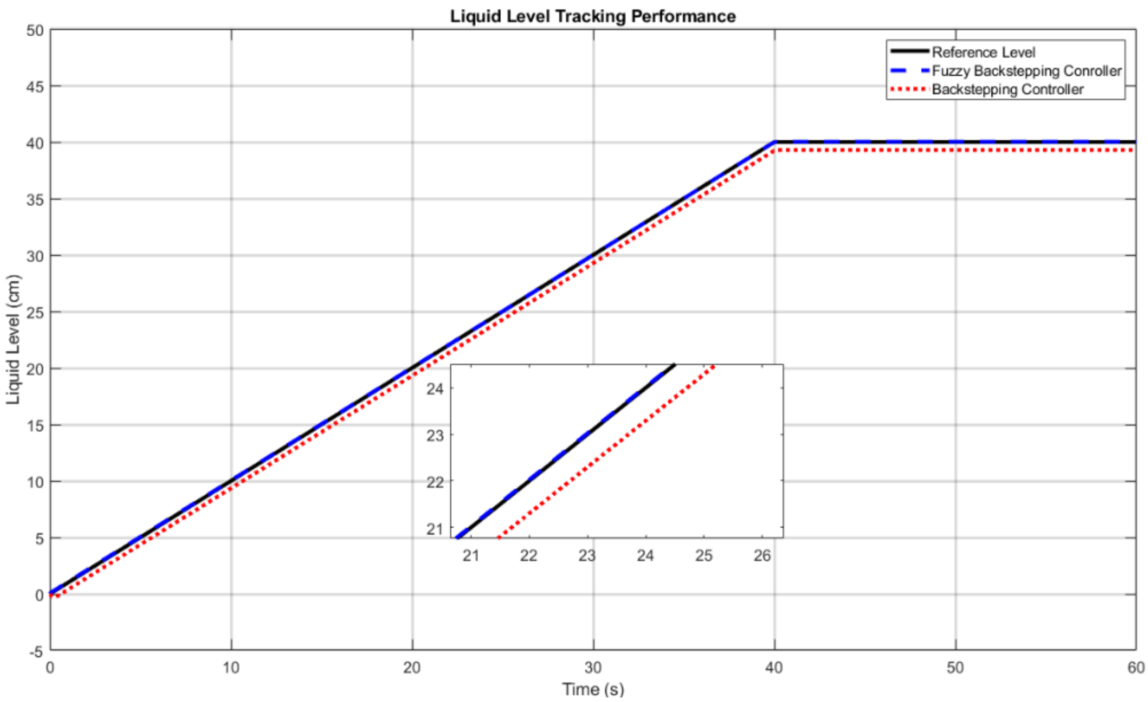


Figure 7. System responses for tracking.

The performance characteristics of the controllers are shown in Table 3. This table provides the steady-state error (e_{ss}), the rise time (t_r), the peak time (t_p), the settling time (t_s), and the overshoot (M_p%) for the classical backstepping controller and the fuzzy backstepping controller. These values' improved or deterioration percentages are shown with the up or down arrows.

The e_{ss} plays an important role for establishing the controller performance. It shows the tracking performance to the reference value of the output of the system. The accuracy, stability, efficiency, and the security of the system highly depend on this value. It is obtained with the error between the reference input signal applied to a control system and the output of the system after it settles into a steady state. The classical backstepping controller guarentees the asymptotic stability not the exact value, so it generally has steady state error. As can be seen from Table 3, fuzzy backstepping controller is 100% effective on the steady state error. The t_r is achieved by taking the time between the signal value crossing 10% value to 90% value. Whereas the classical controller seems as advantageous, it does not reach the reference value, which is the most fundamental objective of the controller. Besides, the rise and settling time can be reduced for the fuzzy controller by waiving the overshoot. The t_p and M_p% are not calculated for the classical controller as the signal has not overshoot. These values are shown as Non-Applicable (NA) in the table. Settling time is NA too, as this dynamic response does not reach the reference value. Additionally, t_p and t_s are acceptable and the overshoot is only 1.7% for the fuzzy backstepping controller. Consequently, as can be seen from the table, the fuzzy backstepping controller overcomes the staeady state error with a little overshoot and a little delay.

Table 3. Performance parameters for the controllers

	Classical Backstepping Controller	Fuzzy Backstepping Controller	Improvement
e_{ss} (cm)	1.94	5*10^{-6}	↑100%
t_r (s)	0.377	0.69	↓45%
t_p (s)	NA	0.9	NA
t_s (s)	NA	1.2	NA
M_p(%)	NA	1.75%	NA

5. Conclusion

This paper presents a fuzzy backstepping controller for the liquid level system to improve the system performance. The transfer function and state-space model of the system have been obtained. The proposed controller has been compared with the classical backstepping controller. The motivation of this study is to overcome the steady-state error of the system response that emerged with the classical backstepping controller. For this reason, the important coefficient of the backstepping controller has been arranged with the fuzzy logic controller. Adapting to changes and uncertainties in the system, Fuzzy backstepping control can deal with uncertainties and tolerate model uncertainties. The results have revealed that the proposed controller has solved the steady state error and the system response has been optimized.

Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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