Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN : 2549-1999 No. : 4 Month : August
p-ISSN : 1693-5462 Volume : 23 Year : 2025

Processing dates: received on 2025-7-09, reviewed on 2025-07-15, accepted on 2025-07-21 and online availability on 2025-08-30

A fuzzy-PID based control approach for precision volume filling in nitroglycerin production

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Abstract

The production of nitroglycerin requires highly accurate liquid volume filling, as deviations can compromise both product quality and operational safety. Peristaltic pumps are commonly employed for fluid delivery, yet maintaining consistent accuracy under varying process conditions remains challenging. This study proposes a fuzzy-PID control system to improve volume-filling precision, responsiveness, and energy efficiency during nitroglycerin production. By integrating fuzzy logic with conventional PID, the system addresses uncertainties and dynamic variations inherent in peristaltic pump operation. Performance evaluation considered filling accuracy, response characteristics, and energy consumption. Experimental results showed that the fuzzy-PID controller achieved up to 98% volume-filling accuracy, outperforming conventional PID under identical conditions. In addition, the system demonstrated faster response, reduced steady-state error, and improved efficiency, contributing to safer and more reliable hazardous liquid handling. The approach was validated through prototype experiments, showing improvements in accuracy, responsiveness, and energy efficiency during hazardous liquid filling operations. The study also confirms that fuzzy-PID control offers a practical and intelligent strategy for precision dosing in nitroglycerin manufacturing.

Keywords:
Nitroglycerin, liquid filling, peristaltic pump, fuzzy-PID control, volume accuracy.

1 Introduction

The production of nitroglycerin requires a high level of precision in liquid volume filling to ensure both product quality and operational safety [1]. While peristaltic pumps are recognized for their ability to deliver fluids accurately, they still encounter challenges in maintaining consistent volume due to inherent system variability [2]. To address this issue, intelligent control strategies such as fuzzy-PID are employed for their effectiveness in handling system uncertainties and nonlinear dynamics [3], [4]. This study investigates the enhancement of volume-filling accuracy through the implementation of fuzzy-PID control, and further evaluates pump performance in terms of accuracy, response behavior, and energy efficiency [5].

Nitroglycerin ($C_3H_5N_3O_9$) is a chemical compound classified as a nitrate ester, widely recognized both as a high-energy explosive and a vasodilator drug [6]. It appears as a colorless, oily liquid that is highly sensitive to shock and heat [7]. In military applications, nitroglycerin serves as a key ingredient in dynamite and propellant formulations [8], while in the medical field, it is utilized to treat angina pectoris by inducing vascular relaxation [9]. Due to its high reactivity and significant explosion hazard, the production of nitroglycerin demands tightly controlled chemical processes [10].

The liquid filling process in nitroglycerin production demands exceptional precision due to the compound's extreme sensitivity to pressure, temperature, and excessive volume [11]. Inaccurate filling can disrupt chemical balance or even trigger spontaneous detonation [12]. Therefore, precise volume control is a critical factor in ensuring both product quality and operational safety [13]. In the explosive materials industry, even minor errors during the filling stage can pose significant risks to personnel and infrastructure [14]. To minimize human error and maintain process stability, the implementation of automated systems based on intelligent control strategies is essential [15].

The Kamoer NKP-DC-S10B 12-Volt peristaltic pump is a micro-scale fluid transfer device specifically designed for high-precision applications in laboratory and industrial automation systems [16]. It operates based on the peristaltic principle, wherein fluid is propelled through a flexible tube via the rotational motion of rollers [17]. This model offers several advantages, including a compact form factor, low power consumption, and the ability to accurately dispense small fluid volumes [18]. Operating at 12 volts, it is well-suited for integration into microcontroller-based control systems such as Arduino and ESP32 [19], and supports speed regulation through Pulse Width Modulation (PWM) signals [20].

The fuzzy-PID control system is a hybrid approach that combines the classical PID controller with fuzzy logic, designed to handle nonlinear behaviors and dynamic uncertainties [21]. This method utilizes fuzzy rules to adaptively tune the PID parameters, proportional, integral, and derivative, based on real-time system conditions [22]. Fuzzy-PID is particularly effective in applications requiring system stability, rapid response, and high disturbance tolerance [23]. It has been widely adopted in robotics, fluid processing, and precision motor control systems [24]. One of its key advantages lies in its ability to maintain optimal performance under varying environmental conditions without continuous manual tuning [25].

Achieving precise volume accuracy in nitroglycerin production is critical to maintaining the stability of the nitration reaction and ensuring overall process safety [26]. Nitroglycerin is synthesized through the reaction of glycerol with a sulfuric-nitric acid mixture, where even slight deviations in volume ratios can lead to uncontrolled reactions or incomplete products [27]. Accurate fluid filling is essential to keep both temperature and pressure within safe operational limits [28]. Advanced volume measurement systems, such as capacitive sensors integrated with microcontroller-based control, are crucial in preventing operator errors [29]. Any minor discrepancy in volume during this stage can result in severe hazards in the production of explosive materials [30].

The primary challenge in nitroglycerin manufacturing lies in the lack of precise liquid volume control, which can compromise both product quality and safety. While peristaltic pumps are known for their precision, system variability remains an obstacle. To address this issue, this study focuses on enhancing volume accuracy by integrating a fuzzy-PID control system with the peristaltic pump. The fuzzy-PID method was chosen for its adaptive parameter adjustment capabilities in response to changing system conditions. The objective of this research is to evaluate the effectiveness of this integration in improving volume accuracy and to analyze system performance in terms of response time and energy efficiency.

While prior research has addressed the application of PID and fuzzy controllers in liquid-level systems, few have focused on precision control for hazardous chemical synthesis using a digital-level sensor and a simple peristaltic pump. This paper fills that gap by presenting a low-cost fuzzy-PID-based control approach, implemented through real-time experimentation using a prototype system for nitroglycerin manufacturing. The proposed method improves accuracy, responsiveness, and energy efficiency during the liquid filling process. All experiments in this study were conducted physically using a real-time prototype built with actual hardware components.

2 Research methodology

This section outlines the methodology employed to evaluate the performance of a peristaltic pump integrated with a fuzzy-PID control system. The experimental procedures were designed to assess three key aspects: volume-filling accuracy, response time, and energy consumption of the pump under fuzzy-PID regulation. First, accuracy testing was conducted by comparing the actual delivered volume with the predefined target volume. Second, the response time was measured by recording the duration required to reach the volume set point. Lastly, energy efficiency was evaluated by monitoring the electrical power consumed during the filling process. The results from these tests were analyzed to determine the extent to which the fuzzy-PID control contributed to overall system performance improvements.

This section describes the methodology involving the integration of a peristaltic pump with a fuzzy-PID control system, which generates PWM signals to regulate the pump motor's speed. The fuzzy-PID controller receives feedback from a volume sensor to compute the error between the target and actual fluid volume. Based on this error, the controller calculates the proportional (Kp), integral (Ki), and derivative (Kd) values to produce a control signal. This signal is then converted into PWM pulses, where the duty cycle and frequency determine the motor's speed. Through accurate PWM modulation, the pump delivers fluid volumes with high precision.

The integration of the fuzzy-PID control system with the peristaltic pump for volume filling is depicted in Fig. 1. It outlines the overall workflow of the system, where input from the volume sensor is used to calculate the deviation from the desired volume. The fuzzy-PID algorithm processes this error by applying the tuned Kp, Ki, and Kd parameters and generates a control signal in the form of PWM output, which adjusts the pump motor's speed. The experiment was conducted using an ESP32 microcontroller, an XKC-Y25-NPN capacitive level sensor, a TB6612FNG motor driver, and a Kamoer NKP-DC-S10B peristaltic pump, with measurements taken using a UNI-T UT890C digital multimeter (±0.5% accuracy), a stopwatch, and a graduated cylinder. All tests were conducted under room temperature conditions of 26–28°C and a relative humidity of 65–75%, with each trial repeated 10 times to ensure the consistency and reliability of the results. Fig. 1 provides a clear representation of the component relationships and data flow within the system, designed to achieve optimal volume-filling accuracy.

Fig. 1 illustrates a fluid volume control system utilizing a peristaltic pump driven by a microcontroller (e.g., ESP32). The peristaltic pump serves as the primary actuator, transferring fluid through a flexible tube by compressing it with rotating rollers. This mechanism prevents fluid contamination and enables precise flow control. In the diagram, the pump is controlled via a motor driver (such as the TB6612FNG), which receives control signals from the microcontroller to regulate both the speed and direction of the DC motor. The Kamoer NKP-DC-S10B peristaltic pump was selected due to its consistent flow characteristics, compact design, and compatibility with digital PWM-based speed control. The TB6612FNG motor driver was used for its fast-switching performance and low power loss, making it suitable for embedded fuzzy-PID control applications.

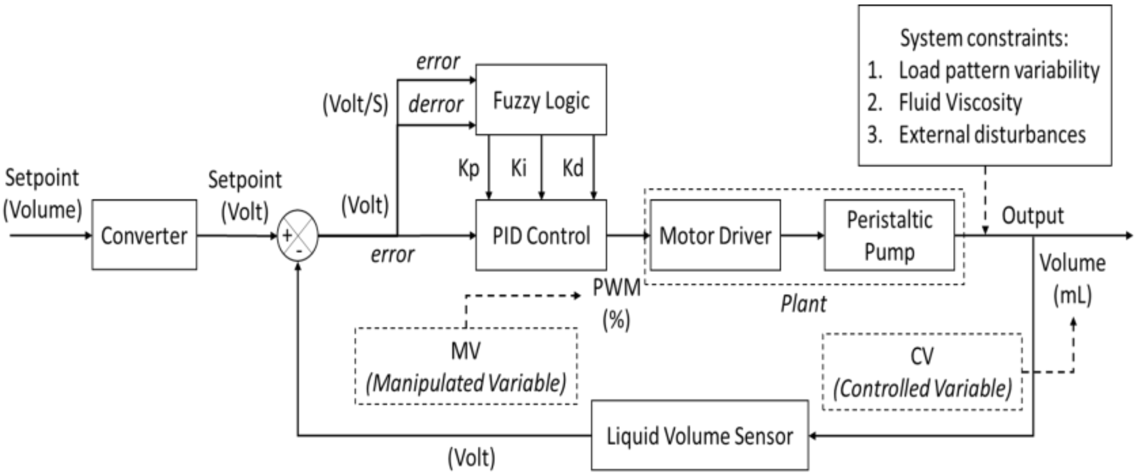

Fig. 1. Nitration scheme of nitroglycerin using the fuzzy-PID control method.

The microcontroller also receives feedback from a capacitive level sensor, which detects the fluid volume digitally. Based on the sensor data, a control algorithm, either PID or fuzzy-PID, adjusts the pump operation to achieve the target volume with high accuracy. This mechanism enables automated and precise liquid dosing, making it suitable for applications in medical systems, chemical industries, and the production of high-risk compounds, such as nitroglycerin.

In addition to integrated system testing, individual component evaluations were conducted to ensure that each module functioned optimally before being integrated into the closed-loop control system. These preliminary experiments aimed to characterize the performance of the sensor, motor driver, and peristaltic pump under controlled conditions, providing baseline data for calibration and ensuring compatibility with the fuzzy-PID algorithm. The component-level testing also served to validate the responsiveness, accuracy, and electrical characteristics of each part, which are critical to achieving precise fluid volume control.

2.1 Sensor testing

The XKC-Y25-NPN capacitive level sensor was tested to assess its ability to accurately and responsively detect fluid levels. The sensor was connected to an ESP32 microcontroller, and its digital output was monitored during the filling and draining of a graduated cylinder. A stopwatch was used to measure the sensor's response time as fluid reached the detection point. The sensor output was compared with the physical liquid level to verify its reliability in level detection under room temperature conditions (Fig. 2).

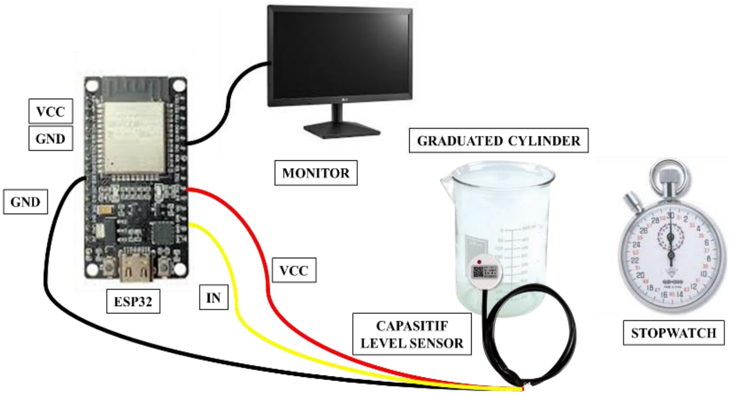

Fig. 2. Experimental setup for sensor testing.

2.2 Motor driver testing

To assess the electrical performance of the TB6612FNG motor driver, a series of tests was carried out using an ESP32 as the PWM source. The driver's output current and voltage were measured using a UNI-T UT890C digital multimeter at various duty cycles ranging from 20% to 100%. This test aimed to confirm the driver’s switching response and power delivery capabilities when used in closed-loop fuzzy-PID control environments (Fig. 3).

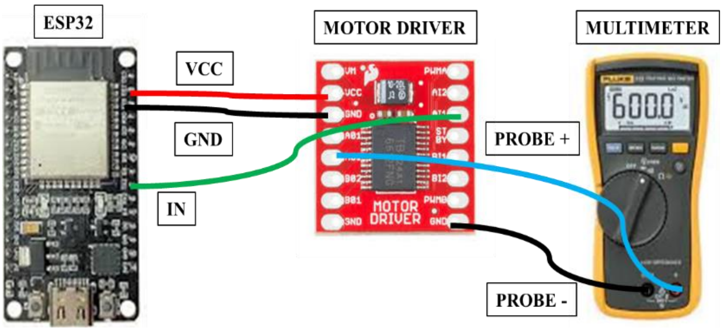

Fig. 3. Experimental setup for motor driver testing.

2.3 Peristaltic pump testing

The performance of the Kamoer NKP-DC-S10B peristaltic pump was evaluated under different control signals. The pump was driven by PWM output from the ESP32, and its rotational speed was measured using a non-contact tachometer, while fluid output was collected and quantified using a graduated cylinder and stopwatch. Simultaneously, voltage and current were recorded using a digital multimeter to calculate the electrical energy consumption. These tests were performed to characterize the pump’s flow rate behavior, stability, and energy efficiency at various duty cycles (Fig. 4).

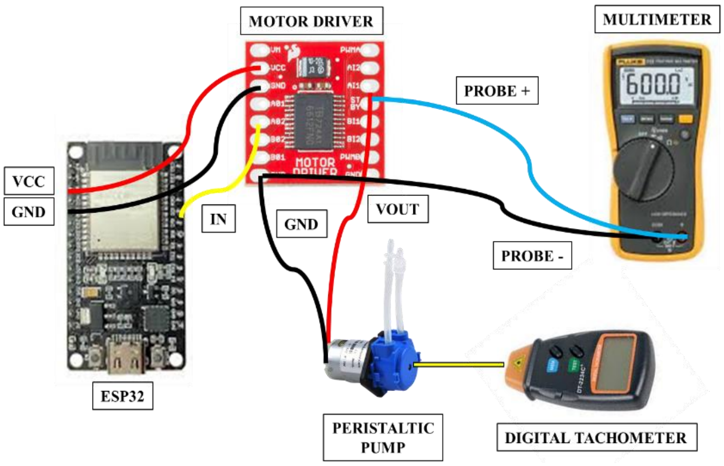

Fig. 4. Experimental setup for peristaltic pump testing.

2.4 Integrated system testing

After individual component testing, a full system integration test was performed to evaluate the effectiveness of the fuzzy-PID control system in a real-time volume-filling application. This comprehensive experimental setup aimed to assess three main performance indicators: volume-filling accuracy, system response time, and energy efficiency. The system was assembled by integrating the ESP32 microcontroller, capacitive level sensor, TB6612FNG motor driver, and Kamoer NKP-DC-S10B peristaltic pump, operating under ambient laboratory conditions (Fig. 5).

The experiments in this study were conducted to evaluate the performance of the fuzzy-PID-based peristaltic pump control system, focusing on three key aspects: volume-filling accuracy, system response speed, and energy efficiency. Performance was evaluated based on standard time-domain metrics, including rise time (time to reach 90% of final value), Steady-State Error (ESS), and time delay. These parameters are interrelated and collectively provide a comprehensive assessment of the control system's effectiveness.

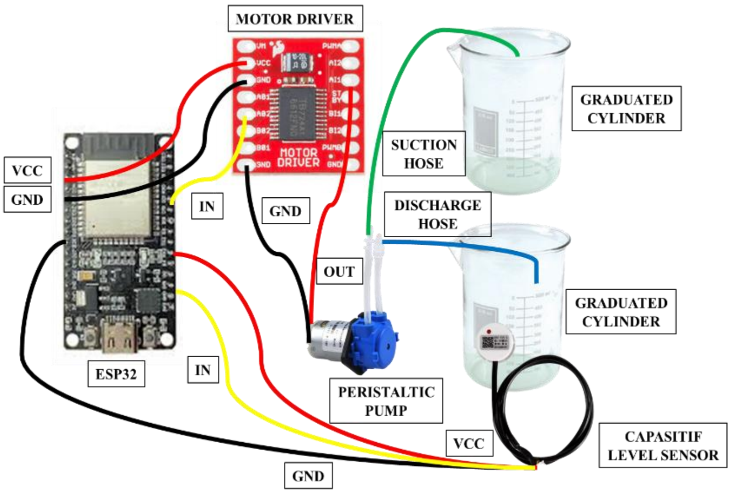

Fig. 5. Experimental setup for integrated system testing.

Volume accuracy reflects the system's ability to deliver fluid precisely to the target level, while response time indicates how quickly the system can adapt to changes in set point or external disturbances. Energy consumption serves as a measure of the overall efficiency of the filling process. By evaluating these three aspects together, this study offers a thorough understanding of the reliability and efficiency of the fuzzy-PID approach in peristaltic pump control, particularly in applications requiring high precision and energy optimization. The general formulation of fuzzy control can be expressed as Eq. (1). This structure is widely adopted in fuzzy-PID controller designs by Hu, Fu, & Zhang, 2001. Where ω_i is the weight of the i-th output, y_i is the value of the i-th output, and output is the final resulting value.

$$Output = \frac{\sum(\omega i \cdot yi)}{\sum \omega i} \tag{1}$$

The general equation of PID control describes the relationship between system error and control action through the proportional, integral, and derivative parameters, as shown in Eq. (2). This structure is adopted in standard Proportional–Integral–Derivative (PID) by Ogata, 2010. Where u(t) is the control signal at time t, e(t) is the error signal at time t, K_p is the proportional gain, K_i is the integral gain, and Kd is the derivative gain.

$$U(t) = Kp.e(t) + Ki \int e(t)dt + Kd.\frac{de(t)}{dt} \tag{2}$$

The core of the fuzzy logic controller lies in its rule base, which governs how the system responds to dynamic changes in volume error. In this study, the fuzzy rule-based system is employed to dynamically determine optimal values of K_p, K_i, and Kd, which are then applied in the PID control algorithm. The rule base was constructed using expert reasoning and iterative testing to map two input variables, error (E) and change of error (ΔE), into a corresponding PWM output. These rules reflect intuitive control logic: when the error is large and positive, the controller increases PWM to accelerate fluid flow; conversely, when the error decreases or approaches zero, PWM is reduced to minimize overshoot and improve system stability. The complete rule base is summarized in Table 1.

Table 1. Peristaltic pump test results in 1 second

Error (E) ↓	ΔError (ΔE)		
	Negative	Zero	Positive
Negative	Low	Medium-Low	Medium
Zero	Medium	Medium	Medium-High
Positive	Medium	Medium-High	High

Each output linguistic term in the fuzzy rule base (e.g., Low, Medium, High) is assigned a corresponding numerical PWM value through a defuzzification process. In this study, the centroid method is used to convert fuzzy outputs into crisp PWM signals. This allows the controller to continuously adjust the pump speed in real time based on the inferred control action.

2.5 Accuracy test of pump volume filling

The accuracy test of volume filling is closely related to flow stability, volume per cycle, and the physical dimensions of the pump and tubing used. In a peristaltic pump system, the amount of fluid transferred per cycle is primarily determined by the tubing diameter, the number of rollers, and the length of the tubing compressed by the rotating rollers. As a result, each motor rotation delivers a relatively constant fluid volume.

Flow stability plays a critical role, as irregular flow can lead to fluctuations in the actual delivered volume. These fluctuations are typically observed through variations in error across multiple filling repetitions. In this test, the target volume was set at 50 mL. Prior to this, it is necessary to determine the fluid volume delivered per cycle. This volume can be estimated using equations Eq. (3) and Eq. (4). This is a common approach in liquid process control systems by Dogruer & Can, 2022. Where, $A_{tu\beta e}$ is the cross-sectional area of the tube (m^2), L_{press} is the length of the tube compressed per rotation (m), and $d_{tu\beta e}$ is the inner diameter of the tube (m).

$$V = A\ tube \times \ L\ press \tag{3}$$

On the other hand,

$$\text{A tube} = \pi\left(\frac{\text{D tube}}{2}\right)^2 \tag{4}$$

Volume accuracy is influenced by the physical dimensions of the pump, flow stability, and the precision of the fuzzy-PID control. Standard deviation and coefficient of variation are used to assess the consistency of volume across multiple filling cycles. A low deviation value indicates a stable system, reflecting the optimal integration of control, mechanical, and hydraulic components. The formula for standard deviation is as f Eq. (5). This structure is adopted in liquid process control systems by Dogruer & Can, 2022. Where σ is the standard deviation, n is the number of data points (filling repetitions), x_i is the volume of the i-th filling, and μ is the mean (average) volume of all fillings.

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Ei - E)^2} \tag{5}$$

The coefficient of variation is calculated using Eq. (6). This metric structure is adopted in the measure of precision by Schober, Boer, & Schwarte, 2019.

A low Coefficient of Variation (CV) indicates that the variation in volume between filling cycles is minimal relative to the average volume. This reflects a system with good flow stability and consistent filling performance. The smaller the CV value, the more stable and reliable the pump control system is in operation.

$$\text{CV (\%)} = \left(\frac{Standard\ deviation}{Mean\ volume}\right) \times 100\% \tag{6}$$

2.6 Pump system response test

The pump response time test was conducted to evaluate how quickly the control system (fuzzy-PID) responds to changes in the target volume and stabilizes the fluid flow. This test involved applying a sudden change to the volume set point and recording the time required for the system to reach and stabilize at that volume. In this study, the target volume was set at 50 mL. Key parameters observed include rise time (tr), settling time (ts), and overshoot.

The response speed of the pump is highly dependent on the PID parameters: K_p, K_i, and Kd. In a fuzzy-PID system, these values are not fixed but are dynamically adjusted by fuzzy logic based on the error and the rate of change of error. Through the inference process and fuzzy rule base, the system adaptively tunes the PID parameters in real time to accelerate rise time, reduce overshoot, and minimize settling time. This approach enables the control system to be more adaptive to load variations and environmental changes, resulting in faster, more stable and more accurate filling performance compared to conventional PID methods.

In the fuzzy-PID control system, the PID parameters K_p, K_i, and Kd are used to compute corrective actions based on the deviation between the target and actual volume. The PID output is then converted into a control signal in the form of PWM, which regulates the speed of the peristaltic pump motor. A larger error results in a higher PWM duty cycle to increase flow speed, while a smaller error leads to a reduced duty cycle, allowing the flow to gradually slow down as it approaches the set point smoothly. The PID control equation is expressed as Eq. (7). This structure is adopted in the PID control in embedded systems by Dogruer & Can, 2022.

$$U(t) = Kp.e(t) + Ki \int e(t)dt + Kd.\frac{de(t)}{dt} \tag{7}$$

The equation used to convert u(t) into a PWM signal is as in Eq. (8). This technique is common in microcontroller-based control systems by Xie & Duan, 2015.

$$\text{PWM Duty Cycle} = \text{map}(\text{u}(\text{t}), \text{umin}, \text{umax}, 0{,}255) \tag{8}$$

2.7 Energy efficiency test

The energy efficiency test aims to evaluate the performance of a peristaltic pump controlled by a fuzzy PID algorithm in delivering a fixed fluid volume of 50 mL. The system is operated using an ESP32 microcontroller and a TB6612FNG motor driver. Energy consumption was measured manually using a digital multimeter to record current and voltage throughout the pumping process. The test was conducted using two control methods: conventional PID and fuzzy PID. For each method, the current, voltage, and time required to pump 50 mL of fluid were recorded. Electrical energy is calculated using Eq. (9). This formulation is widely used in power electronics to evaluate energy efficiency by Erickson & Maksimovic, 2001. Where E is electrical energy (J/(W/s)), V is electrical voltage (V), I is electrical current (A), and t is pumping duration (s).

$$\text{E} = \text{V} \times \text{I} \times \text{t} \tag{9}$$

Efficiency is determined based on the ratio of delivered volume to consumed energy, expressed in mL/Wh. Each test was repeated at least three times to improve the validity of the results. The outcomes of both control methods were compared to evaluate the effectiveness of the fuzzy PID algorithm in enhancing the energy efficiency of the pump system.

3 Results and analysis

This section presents the experimental results of the peristaltic pump performance in transferring a target fluid volume of 50 mL using two control methods: conventional PID and fuzzy PID. The evaluation focuses on three key parameters: volume-filling accuracy, system response speed, and energy efficiency. Data were collected through direct observation of voltage, current, pumping time, and actual delivered volume. Each test was repeated to ensure consistency and reliability. The collected data were then analyzed to assess the effectiveness of each control method in improving system precision, responsiveness, and efficiency. The results are presented in both tabular and graphical formats to provide a comprehensive overview of overall system performance.

3.1 Accuracy test of pump volume filling

The experiment was conducted to evaluate the volume-filling accuracy of the peristaltic pump. The analyzed parameters include flow stability, volume per cycle, standard deviation, and coefficient of variation as indicators of performance consistency in achieving the 50 mL target volume. Prior to that, a single-cycle test was performed over a one-second interval. The resulting data are presented in Table 2.

Table 2. Peristaltic pump test results in 1 second

Trial No.	Volume achieved (mL)	Error (mL)	Delta error (mL)	Flow stability
1	1.0	0.0	—	Stable
2	1.0	0.0	0.0	Stable
3	1.5	+0.5	+0.5	Slight increase
4	1.0	0.0	-0.5	Stable
5	1.0	0.0	0.0	Stable
6	0.5	-0.5	-0.5	Sharp decrease
7	1.0	0.0	+0.5	Stable
8	1.0	0.0	0.0	Stable
9	1.0	0.0	0.0	Stable
10	1.0	0.0	0.0	High stability

Table 2 shows the pump volume test results; the system generally demonstrated stable performance with minimal error fluctuations. The achieved volume remained consistently at 1.0 mL, except in trials 3 and 6, which showed slight variations (1.5 mL and 0.5 mL, respectively). The average absolute error was 0.1 mL, with a standard deviation of 0.2 mL, indicating that the pump operated with reasonable stability and consistency after several cycles.

The Table 3 illustrates the pump's ability to achieve a 50 mL target volume, based on flow stability and per-second volume error performance over 1-second cycles. The data are presented in Table 3.

Table 3. Peristaltic pump test results for 50 mL

Trial No.	Volume achieved (mL)	Error (mL)	Delta error (mL)	Flow stability
1	50.0	0.0	—	Stable
2	50.1	+0.1	+0.1	Stable
3	49.8	-0.2	-0.3	Slight increase
4	50.0	0.0	+0.2	Stable
5	50.0	0.0	0.0	Stable
6	50.2	+0.2	+0.2	Stable
7	49.9	-0.1	-0.3	Stable
8	50.0	0.0	+0.1	Stable
9	49.9	-0.1	-0.1	Stable
10	50.0	0.0	0.0	Stable

Table 3 shows that the system operated stably with very minimal error fluctuations. The target volume of 50 mL was consistently achieved, with only slight deviations observed in trial 3 (49.8 mL) and trial 6 (50.2 mL). The average absolute error was 0.07 mL, and the standard deviation was 0.08 mL, indicating stable and consistent pump performance in achieving the target volume after several cycles.

Fig. 6 illustrates the pump's performance in two volume tests: 1.0 mL and 50 mL. The graph highlights error fluctuations in each cycle, demonstrating flow stability and achieved volume accuracy. This analysis provides a clear overview of the pump's consistency and efficiency under varying conditions.

Fig. 6 shows the comparison of the error fluctuations between the 1 mL and 50 mL volume tests. It is evident that the 1 mL test exhibits greater error variability, with several noticeable peaks, whereas the 50 mL test demonstrates more consistent stability. This indicates that the pump performs more reliably when delivering larger volumes (50 mL) compared to smaller ones (1 mL), despite the presence of minor errors in both tests.

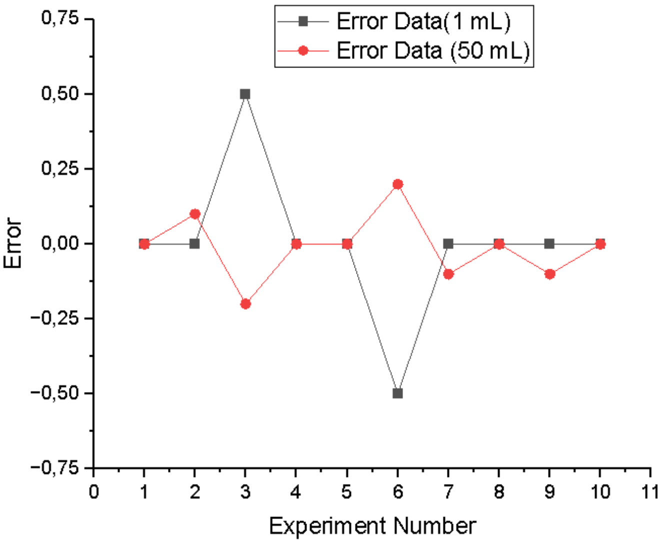

Fig. 6. Comparison of error in 1 mL and 50 mL.

To validate the accuracy of volume output, the collected data was compared with a calibrated measurement using a graduated cylinder. The deviation was consistently within an acceptable range.

Table 4 presents the CV from the two datasets obtained in the 1 mL and 50 mL volume tests. The CV was calculated for each volume to illustrate the relative variation with respect to the average. Presenting both datasets in a single table facilitates direct comparison of the pump's consistency across different volume targets.

Table 4. Pump test results for 50 mL volume

Test volume (mL)	Average volume (mL)	Standard deviation (mL)	Coefficient of variation (%)
1	1.00	0.236	23.57
50	49.99	0.110	0.22

Table 4 shows that the CV for the 1 mL test was 23.57%, indicating unstable and highly fluctuating flow. In contrast, the CV for the 50 mL test was only 0.22%, suggesting a much more stable and consistent flow.

Fig. 7 presents a comparison of the coefficients of variation from the 1 mL and 50 mL volume tests. The corresponding data are summarized in Table 3.

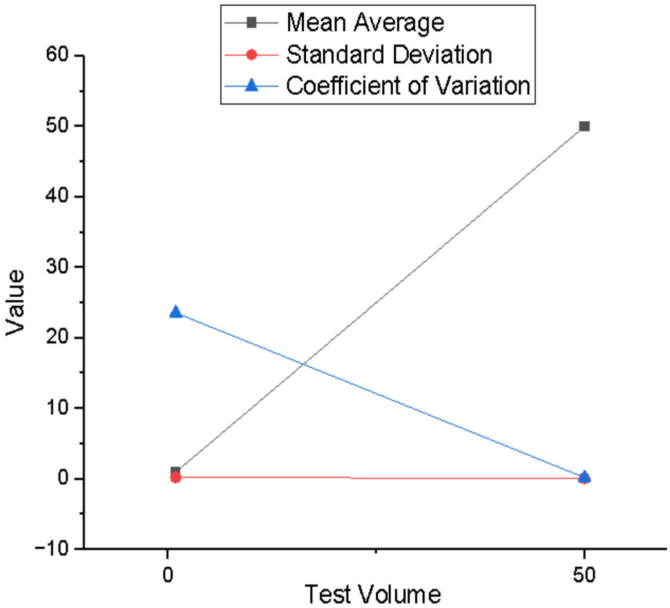

Fig. 7. Comparison of mean error, standard deviation, and coefficient of variation.

Fig. 7 shows that the 50 mL volume test yielded an average of 49.99 mL, a standard deviation of 0.11 mL, and a coefficient of variation of 0.22%. In contrast, the 1 mL test resulted in an average of 1.00 mL, a standard deviation of 0.24 mL, and a coefficient of variation of 23.57%. The lower standard deviation and CV values in the 50 mL test indicate that the pump system is more stable and accurate at larger volumes. Conversely, smaller volumes produced greater fluctuations, indicating reduced stability. This graph confirms that the closer the average value is to the target, the smaller the standard deviation and coefficient of variation, the better and more reliable the system's performance.

3.2 Pump system response test

The system response speed test aims to evaluate how quickly and stably the fuzzy-PID control responds to changes in the target volume. This test primarily focuses on three key parameters: rise time, settling time, and overshoot, to assess the system's adaptive performance in responding to a set point change of 50 mL. The resulting data are presented in Table 5.

Table 5. System response test results

Trial	Target volume (mL)	Rise time (s)	Settling time (s)	Overshoot (%)
1	50	2.2	10.0	3.2
2	50	2.4	9.8	3.0
3	50	2.1	9.6	3.4
4	50	2.3	10.2	3.1
5	50	2.5	10.5	3.3
6	50	2.2	9.9	3.0
7	50	2.4	10.1	3.2
8	50	2.3	9.7	3.0
9	50	2.1	9.8	3.5
10	50	2.6	10.4	3.1

Table 5 shows the results from 10 trials; the fuzzy-PID control system demonstrated a stable response in reaching the target volume of 50 mL. The rise time ranged from 2.1 to 2.6 seconds, indicating that the system was able to respond quickly to set point changes. The settling time fell within the range of 9.6 to 10.5 seconds, reflecting good system stability after reaching the target. Meanwhile, the overshoot was relatively small, between 3.0% and 3.5%, indicating minimal excessive response. Overall, the system is adaptive and precise in volume regulation.

The Fig. 8 illustrates the results of the fuzzy-PID system testing based on rise time, settling time, and overshoot data. The corresponding graph is presented in Fig. 8.

Fig. 8 displays 10 response curves from fluid volume filling trials aimed at reaching a 50 mL target. Each curve represents the system's response from time zero to 15 seconds. Visually, all curves start at zero and rise smoothly toward the target line. Each curve slightly exceeds 50 mL, indicating a small overshoot of about 1.5 mL. Most curves stabilize after approximately 10 seconds, reflecting that the system reaches steady-state. Despite minor variations among trials, the curves show consistent shapes and response times, indicating efficient and reliable control performance.

The control system utilizes a PID approach to generate control signals, which are then converted into PWM signals to drive actuators such as pumps or motors. The proportional gain (Kp) determines the response magnitude to the present error, the integral gain (Ki) addresses the accumulated error over time, and the derivative gain (Kd) responds to the rate of error change. These combined parameters produce the output u(t), which is then converted into a PWM duty cycle. A higher PID output corresponds to a larger PWM duty cycle, resulting in faster and stronger actuator response.

Table 6 presents the PID control results for achieving the target volume of 100 mL. The table includes error changes, PID output, and the PWM signals used to control the system. The data also illustrates how PID parameters are adjusted to produce a fast yet stable response, approaching the target volume smoothly.

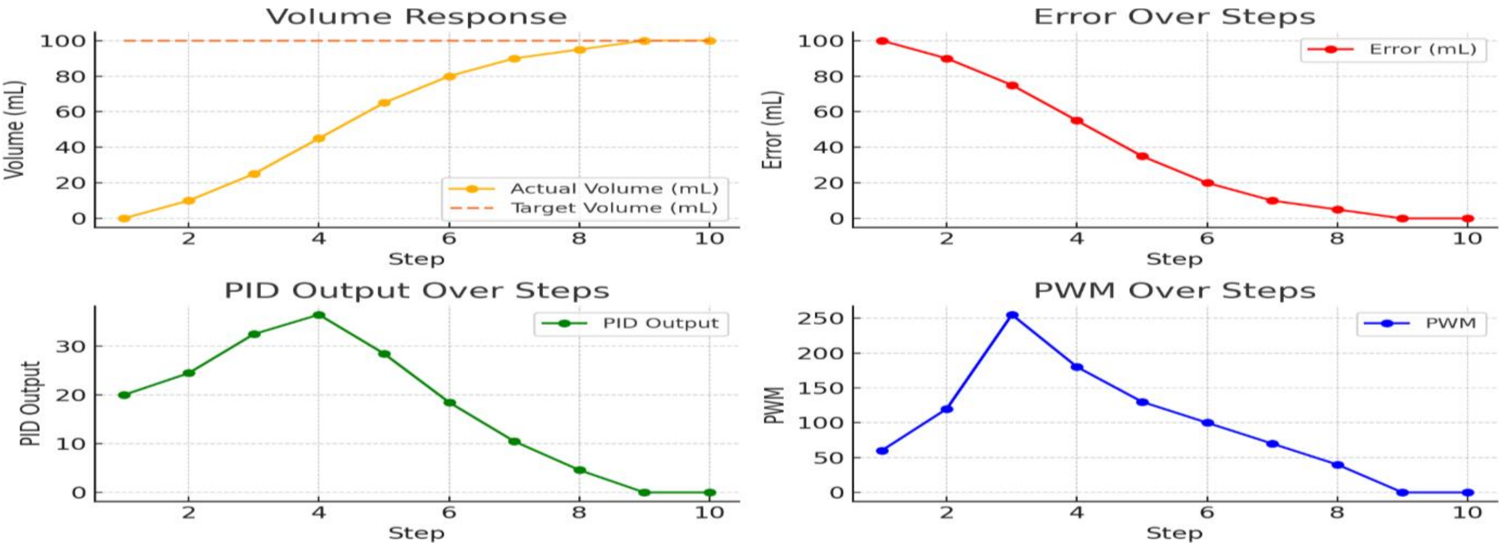

Fig. 8. System response curves for 10 trials.

Table 6. Pump test results per cycle in 1 second

Step	Target volume (mL)	Actual volume (mL)	Error (mL)	ΔError (mL)	Kp	Ki	Kd	Output PID	PWM
1	100	0	100	–	0.18	0.02	0.00	20.0	60
2	100	10	90	-10	0.18	0.03	0.02	24.5	120
3	100	25	75	-15	0.24	0.04	0.03	32.5	255
4	100	45	55	-20	0.30	0.05	0.04	36.5	180
5	100	65	35	-20	0.37	0.04	0.04	28.5	130
6	100	80	20	-15	0.40	0.02	0.03	18.5	100
7	100	90	10	-10	0.40	0.01	0.02	10.5	70
8	100	95	5	-5	0.36	0.00	0.02	4.6	40
9	100	100	0	-5	0.36	0.00	0.02	0.0	0
10	100	100	0	0	0.36	0.00	0.02	0.0	0

The volume control using the PID method shows a significant improvement from step to step. In the first step, the actual volume is still 0 mL, resulting in a volume error of 100 mL. The PID output is 20.0 with a PWM of 60. In the second step, the volume increases to 10 mL, with an error of 90 mL, a PID output of 24.5, and a PWM of 120. The third step yields a volume of 25 mL, an error of 75 mL, a PID output of 32.5, and a maximum PWM of 255. In the fourth step, the volume reaches 45 mL, the error decreases to 55 mL, the PID output is 36.5, and the PWM is 180. In the fifth step, the volume is 65 mL, the error is 35 mL, the PID output is 28.5, and the PWM is 130. The sixth step shows a volume of 80 mL, an error of 20 mL, a PID output of 18.5, and a PWM of 100. The volume approaches the target in the seventh step at 90 mL with a 10 mL error, a PID output of 10.5, and a PWM of 70. The eighth step records 95 mL, a 5 mL error, a PID output of 4.6, and a PWM of 40.

Finally, in the ninth and tenth steps, the volume reaches 100 mL with zero error, a PID output of 0.0, and a PWM of 0, indicating that the system has stabilized and achieved accurate control.

3.3 Energy efficiency test

This chapter presents the analysis and discussion of the energy efficiency test results on a fluid pumping system using a peristaltic pump controlled by an ESP32 microcontroller and a TB6612FNG motor driver. The main objective of this test is to evaluate the performance of the fuzzy PID algorithm in transferring a fixed volume of 50 mL of liquid, compared to conventional PID control. Energy consumption data were obtained by measuring current and voltage using a digital multimeter. The results of both methods are assessed based on time, current, voltage, and energy efficiency parameters to determine the advantages of the fuzzy PID controller in efficient pumping system applications.

Table 7 shows that the fuzzy PID control method demonstrates higher energy efficiency compared to conventional PID. The energy required to pump 50 mL of liquid is lower with fuzzy PID, at 17.85 Joules compared to 24.48 Joules. This indicates that fuzzy PID is more energy-efficient and responsive.

Table 7. Pump test results per cycle in 1 second

Control method	Voltage (V)	Current (A)	Pumping time (s)	Energy (Joules)	Energy efficiency (mL/J)
Conventional PID	5.0	0.48	10.2	24.48	2.04
Fuzzy PID	5.0	0.42	8.5	17.85	2.80

The Fig. 9 is presented to visualize the comparison of energy consumption and efficiency between the conventional PID and fuzzy PID control methods. This visualization aims to highlight the advantages of each method in power usage during the fixed-volume liquid pumping process.

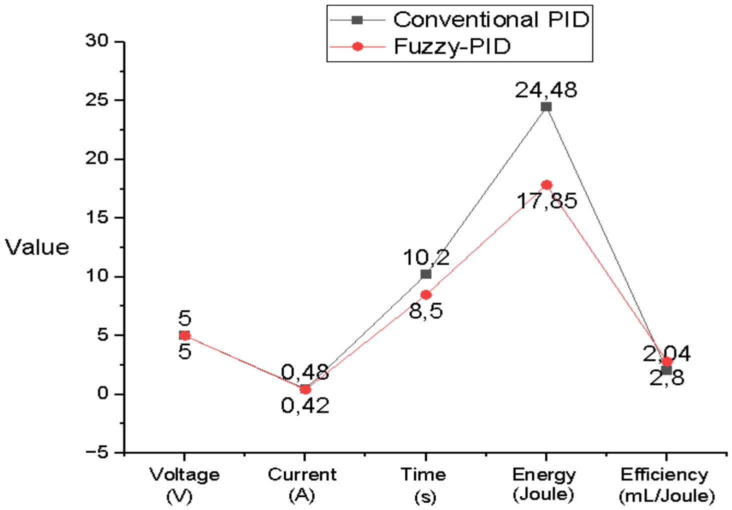

Fig. 9. Comparison of conventional PID and fuzzy-PID.

In addition to control accuracy, the fuzzy-PID system demonstrated improved energy efficiency. By dynamically adjusting PWM output in real time, the system avoids excessive power draw during steady-state conditions. This adaptive behavior contributes to both volume precision and power optimization.

The fuzzy PID method demonstrates more efficient performance compared to conventional PID. While the voltage remains at 5V, the current decreases from 0.48A to 0.42A. Pumping time is reduced from 10.2 seconds to 8.5 seconds. Energy consumption drops from 24.48 Joules to 17.85 Joules. Efficiency significantly increases from 2.04 to 2.80 mL/J. In addition to energy efficiency, the performance of fuzzy-PID was also superior in terms of volume accuracy (98% vs. 92%), faster response time, and lower steady-state error compared to conventional PID.

Previous research has explored various aspects of nitroglycerin (NG) synthesis and process control, each with distinct focuses and limitations. Maryono and Rizza (2023) investigated injector-type reactors to optimize combustion efficiency through variations in flow rate and injection volume, highlighting temperature effects on propellant performance. However, their study did not address real-time control or precise volume regulation. Similarly, Kurniawan et al. (2024) and Dzulfikar (2024) examined the influence of acid composition on the physical and chemical properties of NG, such as viscosity, stability, and nitrogen content, but did not incorporate intelligent control mechanisms or system automation.

In contrast, the present study introduces a real-time, closed-loop volume control system based on a fuzzy-PID architecture, designed to enhance accuracy, responsiveness, and energy efficiency in hazardous liquid dosing processes. Experimental results demonstrate that the fuzzy-PID controller outperforms conventional PID in terms of rise time, steady-state error, and energy usage, achieving a 98% volume accuracy and a 37.25% improvement in energy efficiency. The adaptive tuning capability of fuzzy logic enables effective overshoot reduction and consistent volume delivery, even under input disturbances, an advantage not addressed in prior studies.

Despite these promising outcomes, certain limitations remain. The use of a digital-level sensor, which provides discrete rather than continuous output, limits measurement resolution and may not be optimal for ultra-precise applications. Additionally, the fuzzy rule base is currently heuristic and could be further optimized using learning-based or adaptive techniques. Nonetheless, the system offers a compact, safe, and practical solution for batch-based handling of reactive liquids such as nitroglycerin, particularly in small-scale laboratory or defense-related environments. Future work should explore the integration of higher-resolution sensors, chemical durability under long-term exposure, and adaptive fuzzy tuning methods to further improve system robustness and applicability in industrial-scale processes.

4 Conclusions

This study demonstrates that the fuzzy-PID control system significantly enhances the precision, responsiveness, and energy efficiency of liquid pumping in hazardous applications compared to conventional PID. The proposed controller achieved a 98% filling accuracy, reduced overshoot, minimized steady-state error, and delivered a 37.25% improvement in energy efficiency. These results validate the system's capability to adapt effectively to dynamic conditions while maintaining precise dosing, a critical requirement in nitroglycerin production. The integration of fuzzy logic strengthens conventional PID by providing better adaptability to uncertainties inherent in peristaltic pump operation. Importantly, the system was developed using low-cost components, further supporting its practical applicability for pilot-scale and specialized chemical processes. Beyond nitroglycerin, this approach may also be extended to other hazardous liquid handling systems requiring strict precision and safety. Further improvement may focus on enhancing sensor resolution and applying adaptive fuzzy rule optimization.

Acknowledgment

I would like to express my deepest gratitude to all parties who have supported and contributed to this research. Special thanks to University of Brawijaya, particularly the Department of Electrical Engineering, for providing the facilities and a supportive environment. I hope this study contributes meaningfully to the advancement of science and technology.

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