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Feedforward–Feedback Fuzzy-PID Water Level Control Using PLC and Node-RED IoT

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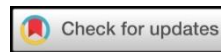
Water Level Control

Feedforward-Feedback

IoT

ABSTRACT

Water level control is vital in industrial processes to maintain operational stability and efficiency, especially against varying disturbances like changes in water inflow and outflow. This research develops a combined feedforward and feedback control system using the Fuzzy-PID method implemented on an Omron CP1H Programmable Logic Controller (PLC) with an IoT-based monitoring interface using Node-RED. An experimental approach was used to test system responses to various disturbances and compare the performance between single feedback control and combined control. Results show that the combined control achieves an average rise time of 18 seconds, faster than the single control's 19 seconds. Settling time is also shorter at 36 seconds versus 42 seconds for single control, and no overshoot occurs with combined control, unlike single control which exhibits overshoot. IoT integration enables real-time remote monitoring and control, enhancing operational convenience and industrial applicability. The system still experiences oscillations due to sensor signal fluctuations, highlighting the need for further improvements in signal filtering and control algorithm optimization. These findings contribute to developing more adaptive and efficient water level control technologies and open opportunities for implementation in automation- and IoT-based modern industries.



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1. INTRODUCTION

In process control industries such as water treatment plants, water level control systems are used to control and process water flow. The water level control system is an important factor affecting production quality and yield [1]. This water level control aims to maintain operational stability and efficiency [2]. However, in maintaining the stability of process control, disturbance is a problem that is found in many industrial environments [3]. The disturbance can be caused by changes in inflow, changes in water discharge rate. Varied disturbances can easily affect the system response, causing control errors and instability in the system [4][5]. Therefore, it is necessary and important to conduct research that focuses on developing efficient and effective controls to overcome the varying disturbances in the control of water control systems [6].

Industrial processes often require control systems to maintain variables such as water, temperature and concentration at desired values for reasons of process safety and product quality [7]. One of the control systems that is familiar in the industrial world to maintain these variables is using Feedback control [8]. Feedback control is a control system that will correct errors to return the output to the desired condition / setpoint. This means, when there is a disturbance in the system, Feedback control will work when the Process Variable (PV) value moves away from the setpoint. Meanwhile, to keep the main variable such as water from disturbance, an extra controller is needed whose job is to push the Process Variable (PV) value back to the setpoint. In this condition, Feedforward control is a control that can overcome the measured disturbance before the PV value moves away from the setpoint. Thus, the disturbance will be corrected more quickly before heading to the Water Level Plant. By combining the two controls above, it can anticipate problems and improve overall performance as in previous research [9][10]. Previously unknown disturbances with this combination of controls can improve performance faster to return to set point and can reduce the use of AC motors as actuators to work more effectively [11].

In controlling a system process, the internet is often used for the needs of society or industry. With the internet, people can communicate with each other very easily and quickly [12]. In this research, the IoT system used is hosting-based with the help of Ngrok software and the Node-RED dashboard as an interface. In a previous journal, it was concluded that the use of IoT in a manufacturing process can reduce Not Good or unfit products and the consistency of the quality of products produced by remotely monitoring and predicting what will happen [13].

In previous research, the control system used was Feedback control and Level Transmitter sensor as Input to determine the PV value and using programmable logic control, namely Programmable Logic Controller (PLC). The study used Fuzzy Logic Tuning control as a Propotional, Integral, Derivative (PID) controller and the Ziegler-Nichols PID Tuning method as a control with a disturbance variation in the form of a DC pump output that can be adjusted from the DA PLC output of 0-6000 resolution which is converted to 0-100%. The result is that Fuzzy-PID is better at responding with minimal overshoot, shorter settling time on average 17.23 seconds while PID averages 78.4 seconds and there is overshoot. However, Fuzzy-PID tends to have a slower rise time of 1-2 seconds than PID control [14].

Based on previous literature studies, the purpose of this research is to present the novelty of Feedforward-Feedback combination system control with the addition of flow sensors as Feedforward control and modeling of water level plants with a system identification approach using PLC as IoT SCADA-based control with Node-RED [15]. Based on previous journals, PID control is more suitable for Singel Input Singel Ouput (SISO) systems [12] and this research will use Fuzzy-PID because it refers to previous research. This research is expected to overcome process control problems such as rise time, stability of the control system process against changes in disturbances and the addition of a Human Machine Interface (HMI) as an interface with tool operation. Using Node-RED as a dashboard makes it easy for users to monitor remotely. Although feedback control has been widely used, this research adds a new approach by incorporating feedforward control, which allows the system to respond to disturbances faster before they affect the setpoint and tuning from Fuzzy-PID. By installing a flow sensor on the output pipe will calculate the amount of flow discharge that was previously unaccounted for making the response faster back to the desired value.

2. RESEARCH METHODS

2.1 Study Design

The research method used in this research is the experimental method. The experimental research method is one of the quantitative methods, used when researchers want to conduct experiments to find the effect of independent variables (effectors) on dependent variables (variables that are affected) under controlled conditions [16]. The stages of the experimental method can be seen in Figure 1.

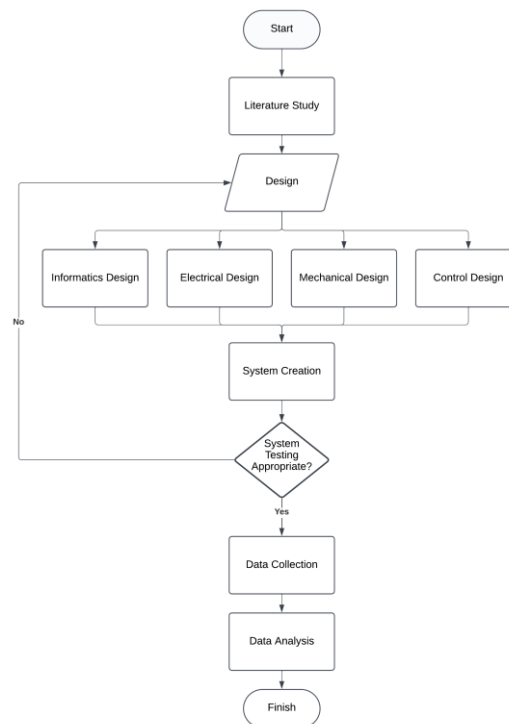


Figure 1. Study Design

Figure 1. Shows the study design. This research begins with finding information about previous research that is relevant to the current research. This information can come from books, journals, proceedings, or the internet. After getting some research journals, the results are analyzed, recorded, and studied. Conclusions from previous research will be used as a background for current research. Then, make a design from mechanical, electrical, informatics and control. Electrical design includes panel design and electrical wiring diagrams, mechanics including Water Level Plant frame design, informatics including SCADA Interface design and control, namely making a control design system that will be implemented in the Water Level Plant. Furthermore, system manufacturing, assembly or assembly of the results of all completed designs. Then, system testing is carried out after all is assembled, such as testing sensors, actuators, Omron PLC controllers, Control and SCADA so that it can be seen which ones can work and cannot work. Before analyzing the data, if the test is appropriate, the next process is data collection. If there is a mismatch during testing, there will be a review from the start of the design. After all systems work properly and data has been collected, the last stage is data analysis and conclusions.

2.2 System Overview

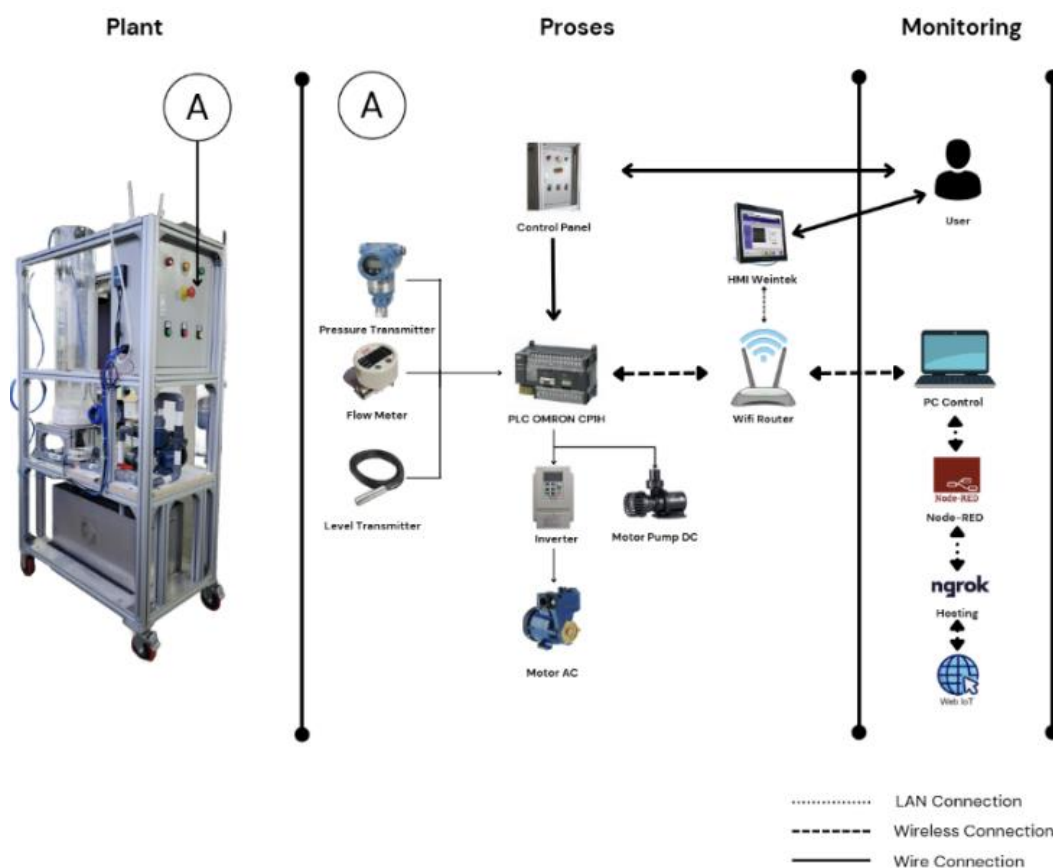


Figure 2. System overview

Figure 2. shows an overview of the entire system. The working principle of several components that enable the use of the Node-RED SCADA dashboard to control and monitor water levels. The level sensor is a sensor that measures the water level using the water pressure in the tank [17]. Pressure transmitter functions as a pump pressure gauge. Flow Meter serves to measure flow using the turbine principle. This flow meter measures the disturbance flow at the inlet and outlet of the Plant. Node-RED can also be used for data loggers to Excel. In addition, the user can control the plant through the control panel, but only for start, stop, drain, and emergency. There are several lights shown on the panel: green for start, yellow for standby and drain, and red for emergency. Ngrok serves as a hosting service, so client PCs can access the Node-RED dashboard through a link that has been hosted by Ngrok. The DC motor functions for disturbances that can be adjusted. The inverter regulates the frequency of the AC Pump so that the speed can be adjusted.

Software used such as MATLAB version 2021 as a calculator to calculate the rules of the Fuzzy Logic Controller. The latest version of Node-RED Dashboard, namely 4.0.8 as a visual-based programming tool for connecting and automating data flows visually and Node.js version 22.13.1 as the basic foundation for being able to run Node-RED.

2.3 Statistical Analysis

Measure Absolute Percentage Error (MAPE) is one of the commonly used metrics in statistics and forecasting to measure the accuracy of a forecasting model. It expresses the absolute average of the percentage error between the actual (true) value and the forecasted (predicted) value [18].

$$MAPE = \frac{1}{n} \sum_{t=1}^n \left| \frac{A_t - F_t}{A_t} \right| \times 100\% \tag{1}$$

with: A_t : the actual value in period t
 F_t : the forecast value in period t
 n : the number of periods or observations
 $|cdot|$: the absolute value

2.4 Mechanical Design

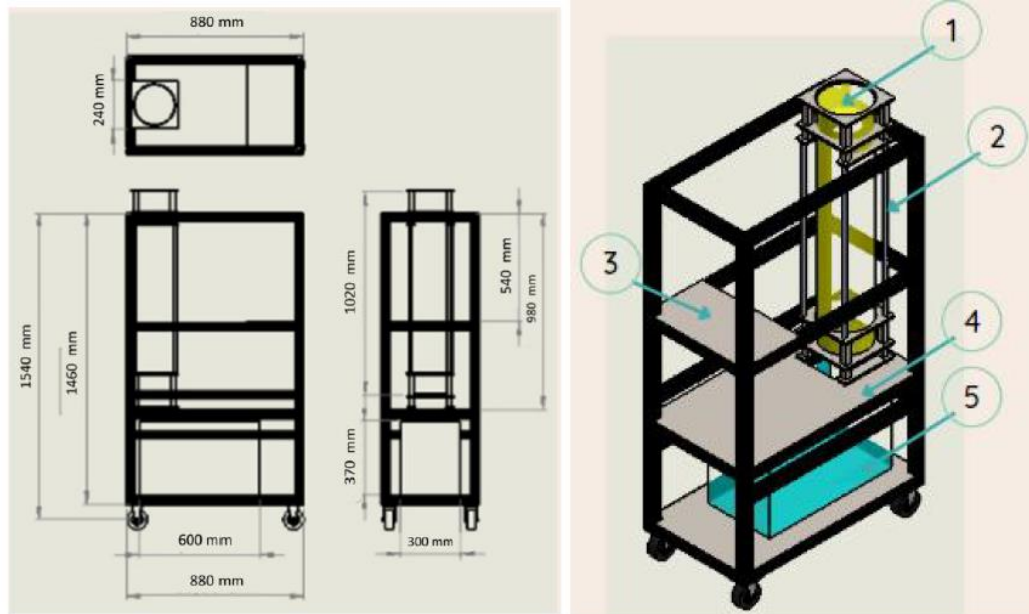


Figure 3. Mechanical Design of Water Level Plant

Figure 3. is the mechanical design of the plant. There are 3 levels starting from level 1, which is the water storage tank, then level 2 is the sensor storage and level 3 is the control panel.

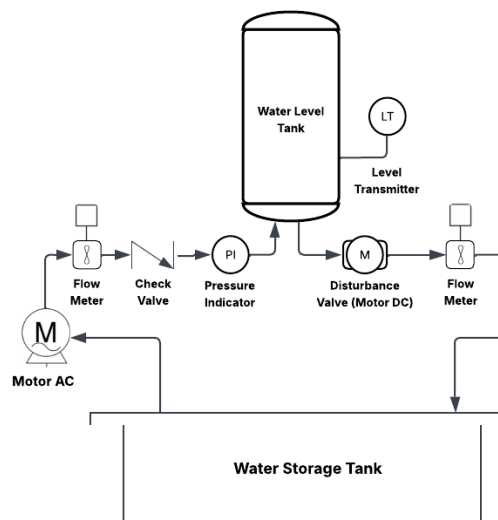


Figure 4. P&ID Water Level Plant

Figure 4. The media used to measure the water level in this tool is a tank that can be changed in height through the Level Transmitter sensor. In this research, actuators namely AC (Alternating Current) and DC (Direct Current) pumps are used to fill the Water Level Tank. The AC pump speed can be adjusted using an inverter, then the DC pump is used as a disturbance, simulating a leaking tank. The water that comes out of the DC pump then enters the Water Storage tank again. The flow meter measures the water discharge then if the incoming and

outgoing water discharge changes it will send a signal to the PLC to immediately adjust the actuator. Pressure sensor as an indicator of water flow pressure.

2.5 Electrical Design

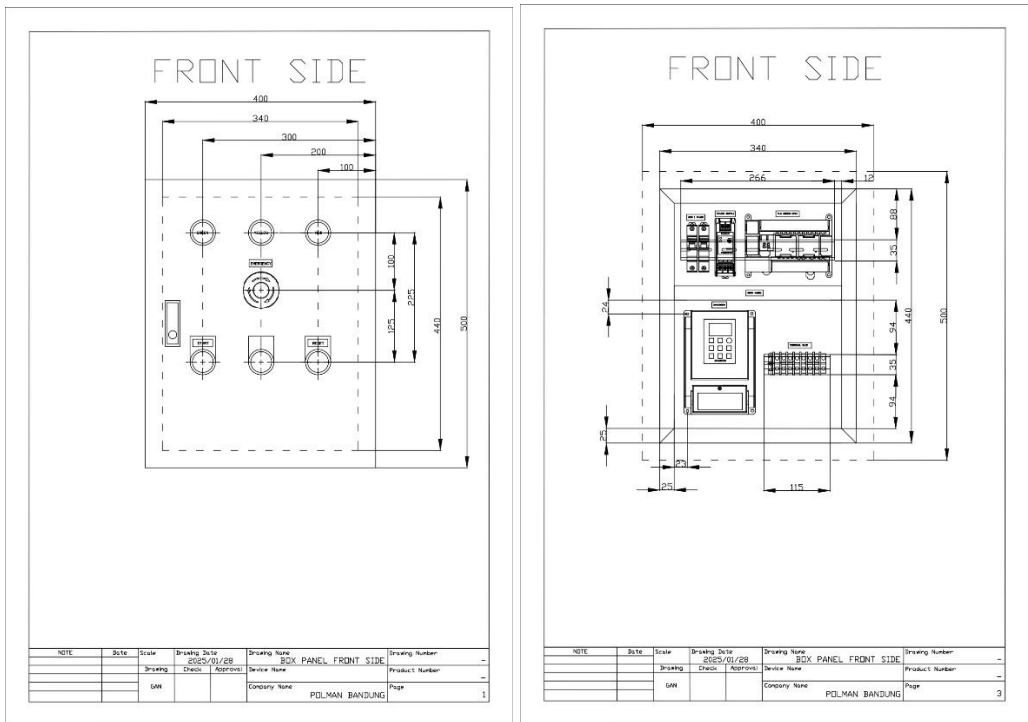


Figure 5. Control Panel Design

In Figure 5. shows the design of the electrical panel in terms of external front view and internal layout. This panel is designed for automation systems that are controlled using a Programmable Logic Controller (PLC), Inverter as a motor regulator, MCB for overcurrent safety and terminal blocks as a link between cables. Control panel design

2.6 Control Design

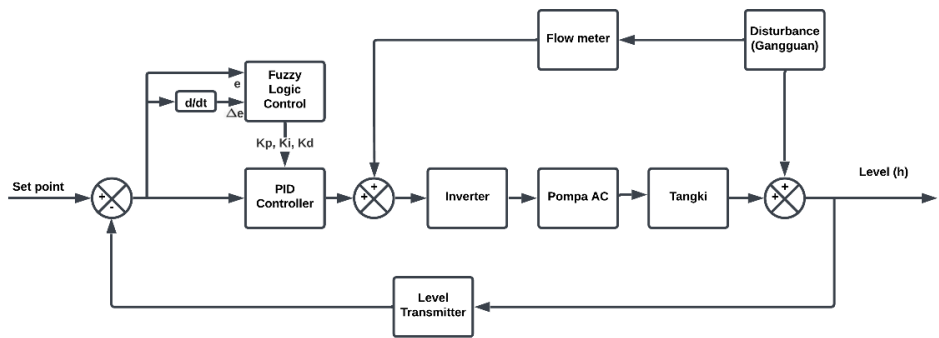


Figure 6. System Block Diagram

In Figure 6. The initial process begins by entering the desired Setpoint value, then the setpoint will be entered into the Fuzzy system. Then the flow meter will detect interference along with the previously inputted PID value. The inverter speed will turn on the pump and fill the tank to get the error and delta error values. The output of the Fuzzy system will produce K_p , K_i and K_d values for the PID parameters, then the inverter speed will adjust to the new PID parameters.

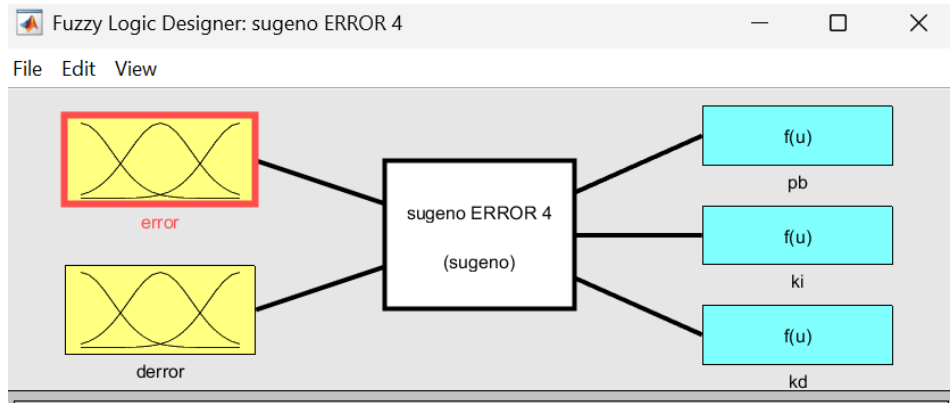


Figure 7. Fuzzy PID Block in MATLAB

Figure 7. shows the MATLAB Fuzzy-PID design block. This design is used to determine whether the fuzzy results produced are in accordance with expectations before being implemented on the PLC. This block has three outputs, namely pb, ti, and td. Fuzzification, Inferent, and Defuzzification are the steps in the fuzzy generation process.

Fuzzification is the process of transforming numerical variables into linguistic variables. The normalized error (e) and delta error (Δe) values of the variables $(-600) - (600)$ into linguistic variables which are labeled as the basic range of each linguistic variable and five Fuzzy subsets namely: NB (Large Negative), NS (Small Negative), ZE (Zero), PS (Small Positive), PB (Large Positive) in order to cover the basic range of each linguistic variable.

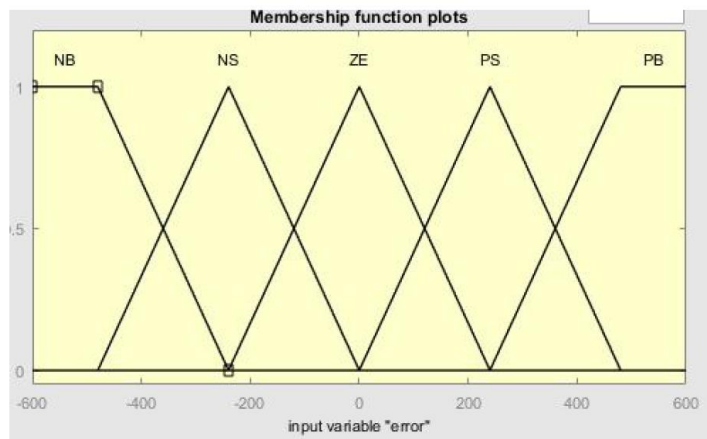


Figure 8. Membership Function Input Error

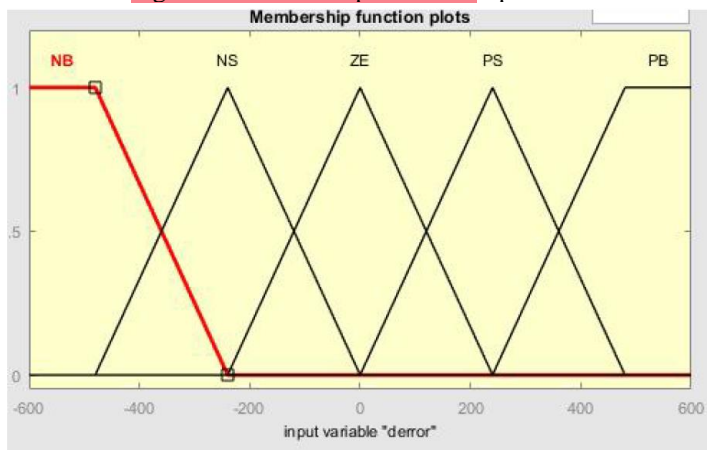


Figure 9. Membership Function Input Delta Error

Fuzzy Inference System, Figures 8 and 9 show the decision matrix used (Fuzzy inference system) in the Fuzzy-PID self-tuning.

dKp dKi dKd	dError				
	NB	NS	ZE	PS	PB
NB	S	B	B	B	B
	B	S	S	S	ZE
	B	ZE	ZE	ZE	B
NS	S	B	B	B	B
	B	S	S	ZE	S
	ZE	ZE	ZE	B	B
ZE	S	B	ZE	B	B
	S	B	ZE	B	S
	ZE	ZE	ZE	ZE	ZE
PS	S	B	ZE	B	B
	S	ZE	S	S	B
	B	ZE	ZE	B	ZE
PB	S	B	ZE	B	B
	ZE	S	S	S	B
	B	ZE	B	ZE	ZE

Figure 10. Rules of Fuzzy Kp, Ki and Kd

Figure 10. Explain table rules of fuzzy logic control which output value is Kp, Ki and Kd. The rules to be the next process into defuzzification. Defuzzification is a method used in the system to find the weighted average value on Fuzzy. The formula used to find the output is using a formula, namely:

$$Zk = \frac{\sum_{i=1}^n \alpha_i Z_i}{\sum_{i=1}^n \alpha_i} \tag{2}$$

with: α_i : the α -i-th predicate
 Z_i : the i-th rules of output antesden
 n : the number of rules used

2.7 Informatic Design

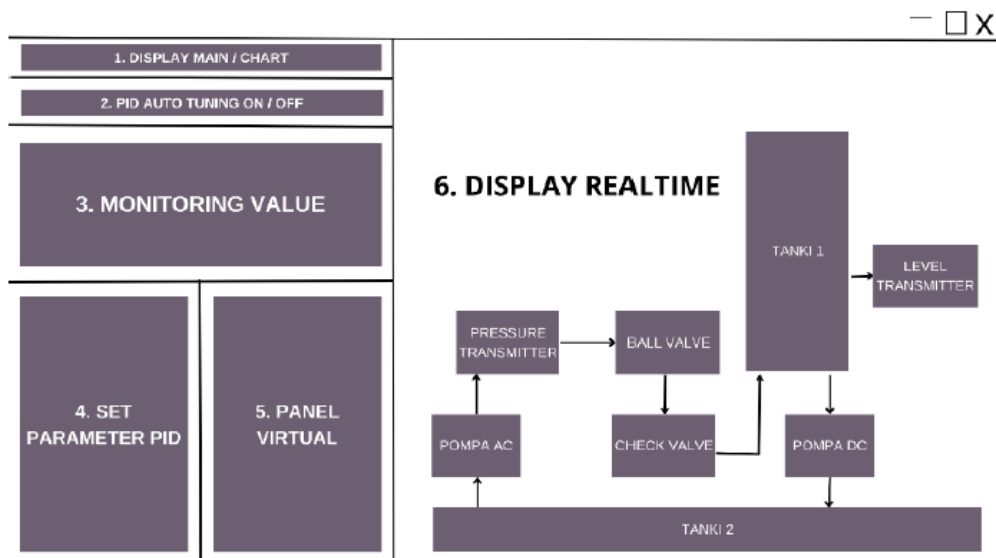


Figure 11. Node-RED Interface Design

Figure 11. shows the display of the system design. This interface is designed to provide PID (proportional integral derivative) control operation and monitoring through an interactive interface. The user can view the main diagram in different tabs, "Menu" to view the graph of the system cost. This diagram helps the user visually understand the performance of the system, especially when the system reacts to changes in setpoint values.

3. RESULTS AND DISCUSSION

3.1 Mechanical Implementation Results

The water level plant was successfully made with a length of 880 mm, a width of 240 mm and a height of 1540 mm. Divided into several levels starting from level 1 for water storage then level 2 is like a sensor and actuator then level 3 is the control panel. Figure 12. is the result of mechanical implementation.

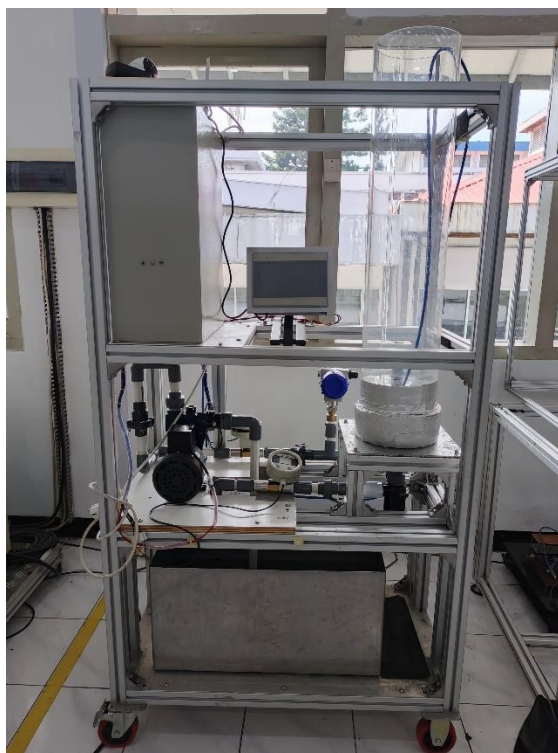


Figure 12. Side view of Water Level Plant

3.2 Sensor Testing Result

3.2.1 Level Sensor

Table 1. Digital value of the level sensor on the tank

Digital value	Actual Value (mm)
157	0
272	100
390	200
509	300
623	400
742	500
857	600

From Table 1. There are digital and actual values (mm) in the water level tank which will be converted into a linear regression as shown in Figure 13.

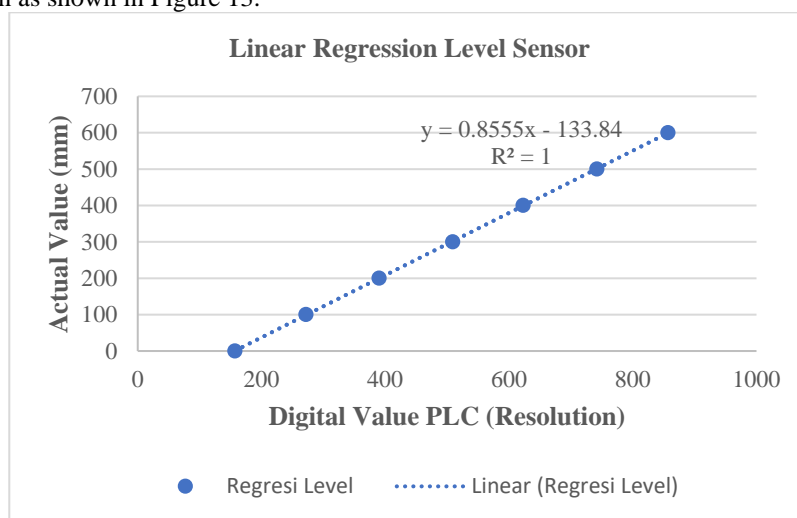


Figure 13. Linear Regression of Level Sensor

In Figure 13. produces a linear equation, namely $y = 0.8555x - 133.84$, then the results of the equation are entered into the PLC program with the level sensor test shown in Table 2.

Table 2. Level Sensor Testing

REAL (cm)	PLC		Average	Error Absolut (%)
	Min Value	Max Value		
10	10.5	10.7	10.6	6
20	20.6	20.8	20.7	3.5
30	30.5	30.7	30.6	2
40	40.7	40.9	40.8	2
50	50.7	50.9	50.8	1.6
60	60.7	61	60.85	1.4
MAPE (Mean Absolute Percentage Error)				2.75

Table 2. is a test of the level sensor by comparing REAL measurements and the results obtained from the PLC system for several distance values in centimeters. The PLC measurement values are recorded in the form of minimum and maximum values, then the average of the two values is calculated. Furthermore, the absolute error for each measurement was also calculated. The Mean Absolute Percentage Error (MAPE) value obtained is 2.75%, which indicates that the PLC is able to produce distance measurements with good accuracy, where the error rate is relatively low.

3.2.2 Flow Out Sensor

Table 3. Digital Value of the Flow Out Sensor

Digital Value	Flow rate Value
9	0
691	1
1050	2
1315	3
1637	4
1908	5
2198	6
2472	7
2703	8
2951	9
3162	10
3387	11
3602	12
3762	13
3959	14
4127	15
4302	16
4322	16.5

From Table 3. There are digital and actual values (mm) in the water level tank that will be converted into a linear regression as shown in Figure 14.

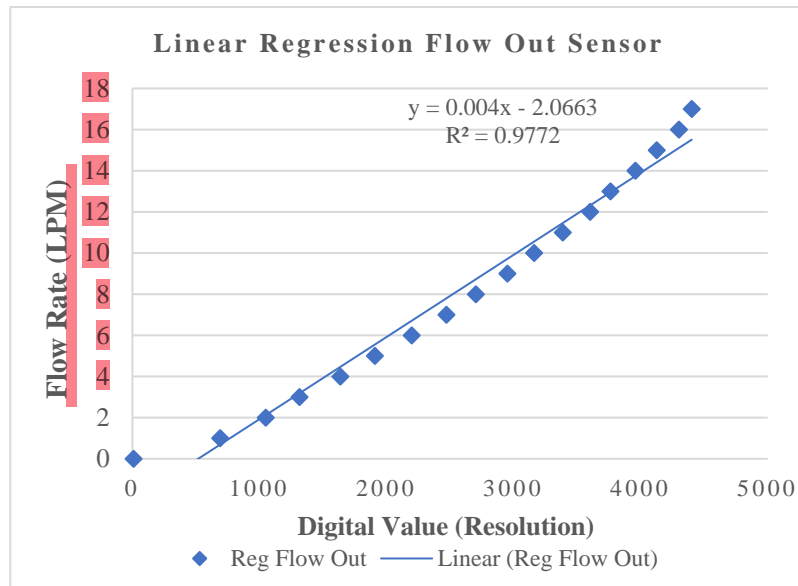


Figure 14. Linear Regression of Flow Out Sensor

Figure 14. produces a linear equation, namely $y = 0.004x - 2.0663$, then the results of the equation are entered into the PLC program by testing the flow out sensor shown in Table 4.

Table 4. Flow Out of sensor testing

REAL (LPM)	PLC		Average	Error Absolut (%)
	Min Value	Max Value		
5	5	5	5	0.00
10	10	10	10	0.00
15	14	15	14.5	3.33
16	15	16	15.5	3.13
MAPE (Mean Absolute Percentage Error)				1.61

Table 4. is a test of the Flow in sensor showing the comparison between the REAL value of flow in units of liters per minute (LPM) and the results obtained from the PLC system. The Mean Absolute Percentage Error (MAPE) value obtained is 1.61%, which indicates that the PLC system has very good accuracy with an error of less than 2% and is classified as low.

3.3 Control System Testing Result

Control testing is carried out with 2 controls, namely single control (Feedback and Fuzzy-PID) and combination control (Feedforward and Feedback with Fuzzy-PID). This test is carried out with the same Kp, Ki and Kd values and is carried out for 2 minutes given different disturbances in the 1st minute (first 60 seconds) from 50% to 100% with the aim of knowing stability if given different disturbances. PID parameters can be seen in Table 5.

Table 5. Parameter of Tuning Fuzzy-PID

Controller Type	Kp	Ti	Td
Fuzzy-PID	4	43	7

In testing the control response, the constants in the combination control, namely Feedforward and Feedback with Fuzzy-PID, are determined based on trial & error as in the book [19]. That is by determining the constant value based on trial & error. The book states that if the constant value causes overshoot in the system response then reduce the value but if the value is less in the system response then add the value little by little. In this study, using a constant with a value of constant of feedforward (Kff) = 10, then the value as a multiplier for the Flow In and Flow out sensor values. The value is entered into the Omron PLC program so as to produce additional values for the Fuzzy-PID output. In Figure 15, the D801 data is the inverter output after adding the constant from the feedforward. From the beginning without feedforward, the output value of the inverter resolution is +4910 after being combined to +4920. This means that the combination of feedback and feedforward has been included in the PLC program.

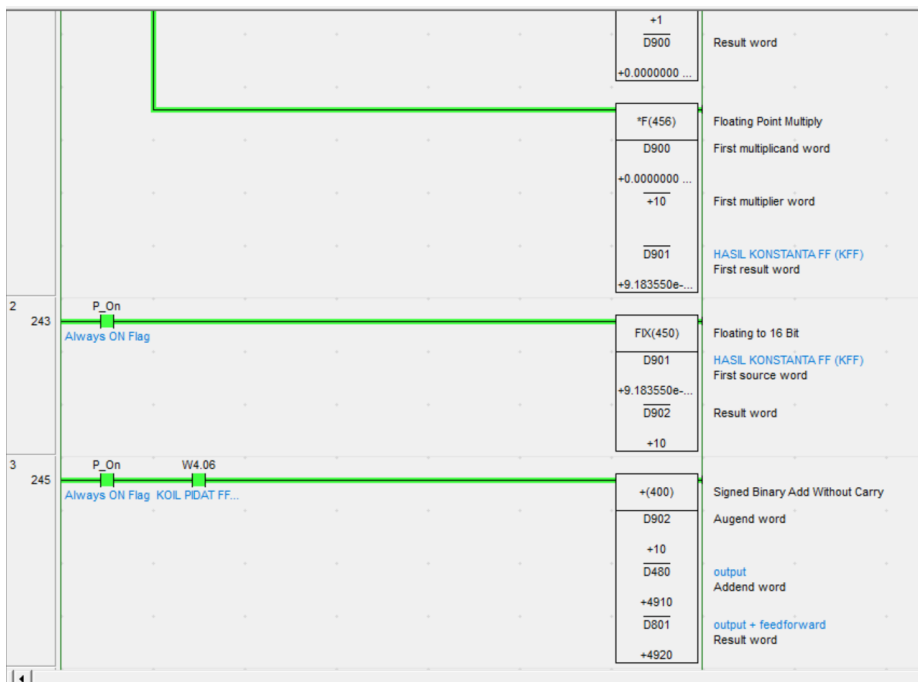


Figure 15. Feedback and Feedforward Combination Program on a PLC

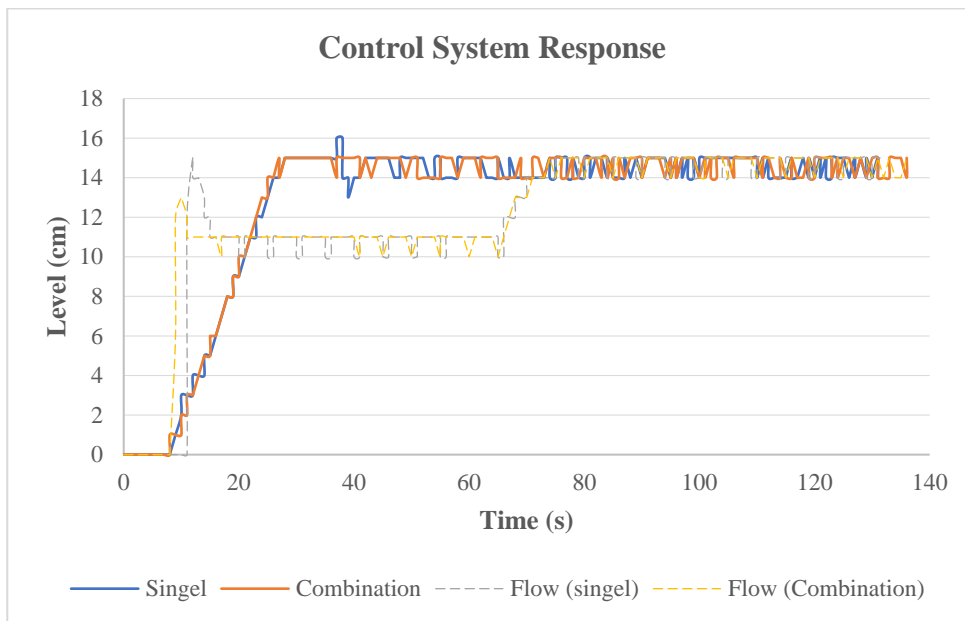


Figure 16. Control System Response testing

Figure 16. is the result of the test response between the two controls, namely Fuzzy-PID with Feedback (Singel Control) and Fuzzy-PID with Feedforward and Feedback (Combination Control). Discussion of Figure 16. can be seen in Table 6.

Table 6. System response characteristics

Self Tuning Fuzzy PID					
Test	Error steady state	Rise Time (s)	Settling time (s)	Overshoot	Oscillation
Singel	0.5%	19	42	Yes	Yes
Combination	0.5%	18	36	No	Yes

In Table 6. the combination method provides better results and is 1 second faster with a rise time of 18 seconds compared to the Singel method in testing Self Tuning Fuzzy PID. With a faster response time and no overshoot, the Combination method is able to provide smoother and more responsive system control. Then in

achieving a steady time or Settling time is 36 seconds faster than single control. In addition, the Combination method is also proven to be able to maintain system stability better when facing changing or increasing disturbances, appearing to show higher adaptability to maintain optimal system performance compared to the Single control method. However, both controls above still have constant oscillations, this occurs due to rapidly changing level sensor readings.

3.4 Informatic Testing Result

3.4.1 Node-RED with PLC Interface Testing

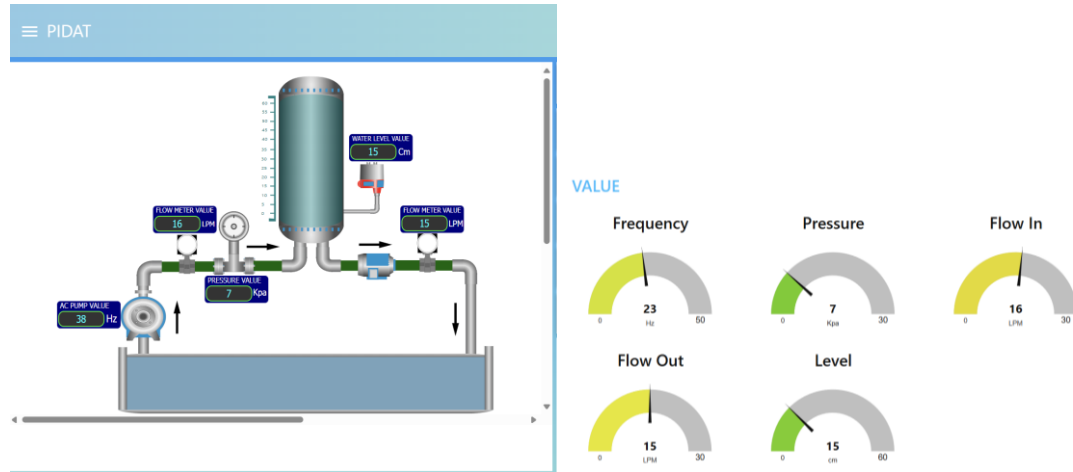


Figure 17. Node-RED Dashboard Testing

Figure 17. shows the test between the Node-RED dashboard and the PLC program. Users can monitor the water level through the level sensor, know the input and output flow through flow in, flow out, know the pressure in the tank with gauge value pressure and can know the speed of the AC motor inflow through the frequency on the inverter.

3.4.2 PC-PLC Data Transfer Speed Testing with TCP Fins

In this speed test, Wireshark software is used to calculate the difference between the sender's address, 192.168.10.6 to 192.168.10.16 as the Omron PLC address using the Fins TCP protocol. Table 7. shows the average transfer speed.

Figure 7. Transfer speed data

No	Features	Input/ Output	Address	Delay (ms)	
1	Sensor	Level	Input	D701	0.000864
					0.010942
					0.030609
					0.069359
					0.031187
					0.000611
					0.070653
					0.010702
					0.020569
					0.030717
Average (ms)				0.027621	
2	Setting Parameter	Kp	Input	D411	0.053796
					0.464394

						0.062664
						0.268633
						0.242599
						0.25245
						0.023951
						0.051414
						0.128076
						0.013556
					Average (ms)	0.156153
						0.223512
						0.283305
						0.254409
						0.179058
						0.258269
3	Indicator	Green Lamp (Run)	Output	W3.08		0.294168
						0.274062
						0.17269
						0.279798
						0.313811
					Average (ms)	0.253308

Table 7. shows that the average speed of the level sensor reading input is 0.027621 ms, then at setting the input value of the Propotional Constant (Kp), the average range is 0.156153 ms and the reading of the light indicator output is 0.253308.

3.5 IoT Testing of Node-RED

In testing the SCADA Node-RED in IoT, testing was carried out with the help of a hosting platform, namely Ngrok, because Node-RED is still based on localhost.

```

ngrok
Load balance anything, anywhere with Endpoint Pools! https://ngrok.com/r/pools

Session Status      online
Account             gailananaibury@gmail.com (Plan: Free)
Version             3.22.1
Region              Asia Pacific (ap)
Latency              28ms
Web Interface       http://127.0.0.1:4040
Forwarding           https://29f7-103-48-27-8.ngrok-free.app -> http://127.0.0.1:1880

Connections
  ttl   opn   rtt   rt5   p50   p90
  89    3     1.35  0.29  0.54  1.57

HTTP Requests
-----
14:21:09.622 +07 GET /red/tours/welcome.js           200 OK
14:21:08.025 +07 GET /icons/node-red/subflow.svg      200 OK
14:21:07.926 +07 GET /vendor/mermaid/mermaid.min.js   200 OK
14:21:06.240 +07 GET /icons/node-red/link-call.svg    200 OK
14:21:06.493 +07 GET /icons/node-red/arrow-in.svg     200 OK
14:21:06.210 +07 GET /icons/node-red/switch.svg      200 OK
14:21:06.493 +07 GET /ui_base/gs/gridstack.min.js     304 Not Modified
14:21:06.291 +07 GET /icons/node-red/parser-html.svg  200 OK
14:21:06.493 +07 GET /ui_base/gs/gridstack.jqueryUI.min.js 200 OK
14:21:06.054 +07 GET /uisettings                     304 Not Modified
    
```

Figure 18. Active Ngrok Command

Figure 18. shows the Ngrok shortcut that is already active and hosted, in Session Status, namely the Web Interface <http://127.0.0.1:1880> is the Node-RED dashboard address which is then hosted by Ngrok to

produce a new address, namely in Forwarding to <https://29f7-103-48-27-8.ngrok-free.app>. After getting a new address, this new address will be tested on another device, here I use a cellphone with its own cellular network. HTTP Request is a request sent by a client, such as a browser or application, to a server to retrieve various resources, such as HTML files, images, or JavaScript scripts. There are several processes such as 304 Not modified which means that there are no changes to the /uisettings parameters on Node-RED made on other devices. This test can be seen in Figure 19.



Figure 19. IoT Water Level Plant Hosting Testing

Figure 19. is an IoT hosting test using another device or mobile phone with a cellular network. Users can set parameters on the plant using a different internet (using their own cellular network data). This means the system is already online and can be controlled remotely. Signaling the Water Level Plant is integrated with the Internet of Things.

3.6 Discussion

While this study has successfully designed stable feedback and feedforward controllers for WWTP aeration systems, challenges in addressing time delays and oscillations due to disturbance characteristics persist. As a step forward in overcoming these limitations and exploring more practical implementations, our subsequent research by Sunarya et al. proposes a feedforward-feedback water level control system utilizing Fuzzy-PID on an Omron CPH PLC, complemented by an IoT-based Node-RED monitoring interface [9]. Our approach demonstrates notable performance improvements: our combined control system achieves a faster rise time (18 seconds vs. 19 seconds) and a shorter settling time (36 seconds vs. 42 seconds) compared to single feedback control. Furthermore, we successfully eliminated overshoot observed in single feedback control, which is crucial for system stability. A key novelty in our work is the utilization of a flow sensor as a feedforward input, enabling more proactive disturbance detection and correction compared to the time delay limitations previously discussed.

These results are in line with the findings in previous research [20] which shows that the use of Fuzzy-PID is able to produce faster settling time and less overshoot than conventional PID, although it has a slightly slower rise time of about 1-2 seconds of optimization. The research focused on optimizing Fuzzy-PID as a single controller with varied disturbances, while this research develops further by adding feedforward control that uses a flow sensor as an additional input, so that disturbances can be detected and corrected more quickly before affecting the water level. The integration of IoT SCADA through Node-RED in this research adds innovation value by providing real-time remote monitoring and control capabilities, which have not been explained in detail in previous studies.

4. CONCLUSION

This research successfully developed a combined feedforward and feedback water level control system using Fuzzy-PID implemented on an Omron CPH PLC, with real-time monitoring via a Node-RED-based IoT dashboard, addressing the need for efficient and stable control against varying disturbances. The system demonstrated improved performance over single feedback control, achieving a faster average rise time of 18 seconds (compared to 19 seconds) and a shorter settling time of 36 seconds (versus 42 seconds). Notably, the combined control eliminated overshoot, contributing to a smoother and more stable response to water flow variations. A key contribution of this work is the integration of a flow sensor as a feedforward input, enabling more proactive disturbance detection and correction before affecting the water level. Furthermore, the IoT integration through Node-RED provides valuable real-time remote monitoring and control capabilities, enhancing operational convenience and industrial applicability in line with Industry 4.0 concepts. Additionally, industrial-scale testing with more complex disturbance conditions and integration with robust IoT platforms are recommended to ensure system reliability and security in real-world industrial environments.

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