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Modelling and Analysis of Ziegler-Nichols PID Tuning on Water Tank Control System

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Abstract

In the industrial world, the water level in the tank is often controlled using a PID controller. The main problem in using a PID controller is the problem of tuning the three PID parameters (Proportional gain, Integral gain, and Derivative gain). In this study, the parameter controller tuning is done using the heuristic tuning method that is applied on the water level plant and the Ziegler-Nichols tuning method that is simulated using MATLAB software. The results of both tuning methods will be compared. To simulate the control system, the water level system in the tank is modeled in the form of a first-order plus dead time modified with the Pade approach. Tuning using the Ziegler-Nichols method produced a good response, where the final value of the water level was the same as the set point value (SSE = 0%) with a settling time of 6.18 minutes.

Keywords: Heuristic, Mathematical modelling, Tuning, Water tank, Ziegler-Nichols

1 Introduction

The Proportional-Integral-Derivative (PID) controller is a conventional controller widely used in various industries to automatically control systems. Although many other modern control methods have been developed, such as the Fuzzy Logic controller [1], adaptive controller [2], genetic algorithm controller [3], and a neural network-based controller [4], the PID controller is still widely used because it has proven reliable in controlling the system. A PID controller is a simple, flexible, and effective system [5]. In addition, the Proportional-Integral-Derivative (PID) Controller has good stability and is easy to implement [6].

The PID controller has three control parameters that must be determined. These three parameters are proportional gain (K_p), integral gain (K_i), and differential gain (K_d). The main difficulty in using a PID controller is determining the values of these three parameters to achieve a stable system quickly and to have the system output (controlled variable) reach the desired value (set point). In practice, these three PID controller parameters are tuned using the Heuristic method (trial and error). This method is widely used in practice because it does not require mathematical equations. The disadvantages of the Heuristic method are that it requires an experienced designer, the process is time-consuming, and there is no guarantee that the correct controller will be obtained [7]. To overcome the weaknesses of this method, the Ziegler-Nichols tuning method was developed [8, 9].

In process control, the three main variables typically controlled are level, temperature, and pressure. For processes that do not require heating, such as water tanks, the primary variable that must be controlled is the water level in the tank. By nature, processes are nonlinear systems. These processes have mathematical models with dead time/time delay. Therefore, these processes can be modeled in the form of First Order plus Dead Time (FOPDT) [10] or First Order plus Time Delay (FOPTD) [11]. Unfortunately, the presence of this dead time/time delay makes it difficult to simulate control systems. Therefore, this dead time/time delay is modified using the Pade approach [13, 14].

In this study, the water level system in the tank will be controlled by a PID controller. The three controller parameters, namely K_p, K_i and K_d, are tuned using a heuristic method. The results of this tuning will be compared with the results of tuning using the Ziegler-Nichols method, simulated using MATLAB software. To simulate this water level control system, the system is modeled in the form of a modified FOPDT using the Padé approach. All simulation results will be analyzed comprehensively and compared with the results of heuristic tuning to provide the most effective control system performance.

2 Literature Review

In general, a control system is used to regulate the output of a system (plant). The control system is correcting the plant output by controlling variables that can affect the plant. The control system works by comparing the current process value and the desired value (set point).

A. PID

In engineering practice, PID control is one of the most significant control systems and consists of proportional, integral, and differential control. PID is a linear controller that produces control outputs based on system feedback. The input of the PID controller is obtained by calculating the error between the desired value (set point) and the actual value (process variable). The output of this PID controller is shown in the following equation (1) [5].

$$u(t) = K_p e(t) + K_i \int e(t) + K_d \frac{de(t)}{dt} \tag{1}$$

where $u(t)$ is the output of the controller, $e(t)$ is the actual error, while K_p, K_i and K_d are gain of Proportional (K_p), Integral (K_i) and Derivative (K_d). The schematics of the equation are shown in Fig. 1.

These three components have their respective roles. If the Proportional gain (K_p) value is large, it will produce a larger output with the same error. However, proportional reinforcement that is too high can lead to system instability. In contrast, low proportional gain results in smaller outputs for the same fault, making the controller less sensitive. Integral gain (K_i) reduces the time to reach the system endpoint and eliminates some of the steady state errors (SSE).

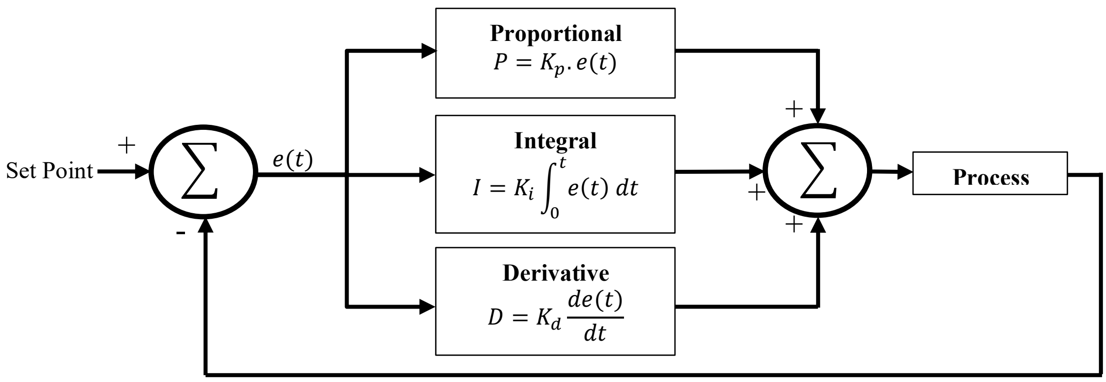


Figure 1. Schematic of PID Controller

However, the higher the integral gain value, the shorter the time for the system to reach the steady state point (T_s). The integral control will accumulate all previous errors. While the Derivative Gain (K_d) is a differential control that improves the setup time and stability of the system [6].

B. Modelling

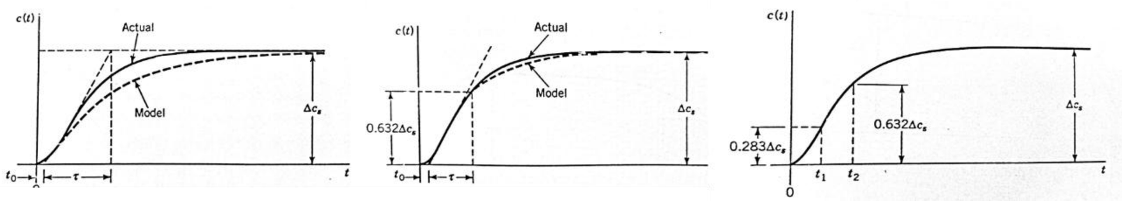
If the model is unknown, experiments are carried out on the system. The First-Order Plus Time Delay (FOPTD) or the First-Order Plus Dead Time (FOPDT) is one of the methods used for system modeling [8]. The FOPDT model is often used because it provides a good balance in explaining the process's behavior. The FOPDT model is the right choice for a wide range of higher-level industrial process needs, as simulation is much easier. The FOPDT model has transfer functions as stated in equation (2) [9-11].

$$G_p(s) = \frac{Ke^{-t_0 s}}{\tau s+1} \tag{2}$$

where t_0 is dead time, and τ is the time constant. There are three methods for estimating the dead time and time constant. They are Fit 1, Fit 2, and Fit 3 [12] that are shown in Fig. 2. The value of the dead time and time constant is stated in equations (3) and (4).

$$\tau = \frac{3}{2}(t_2 - t_1) \tag{3}$$

$$t_0 = t_2 - \tau \tag{4}$$



(a) (b) (c)

Figure *2.* FOPDT model parameter by; (a) Fit 1, (b) Fit 2, (c) Fit 3

The FOPDT method still has a delay element. Padé approximation is used to replace the delay element ($e^{t_0 s}$). Padé approximation is a mathematical technique with rational fractions to make it easy to analyze/tune. This model uses controller tuning rules and can be used as a replacement model in computational simulations for optimization purposes [13]. The approximations are shown in equation (5).

$$e^{-t_0 s} = \frac{1-\frac{t_0}{2}s}{1+\frac{t_0}{2}s} \tag{5}$$

Some control system designs require a rational transfer function. Padé's approximation provides a specific type of approximation to dead time in a continuous process system.

C. Ziegler Nichols Methods

Heuristic is the method that has evolved based on practical implementations or simulations [15]. The use of heuristic algorithms allows for automatic search of optimal PID (K_p, K_i, K_d) parameters without the need for an exact model to speed up the tuning process and improve control performance. If the model is unknown, experiments are carried out on the system. As explained in the introduction, the weaknesses of the heuristic method (trial and error) are overcome by using the Ziegler-Nichols tuning method. This method is used to determine in the real-time process control system [14]. The Ziegler-Nichols theorem for each K_p, K_i, K_d is shown in Table 1. Curve response for the Ziegler-Nichols Method is shown in Fig. 3.

Table 1. Ziegler Nichols Theorem

Controller	K_p	T_i	T_d
P	$\left(\frac{\tau}{t_0}\right)$	0	0
PI	$0.9\left(\frac{\tau}{t_0}\right)$	$\frac{t_0}{0.3}$	0

PID	$1.2\left(\frac{\tau}{t_0}\right)$	$2\ t_0$	$0.5\ L$

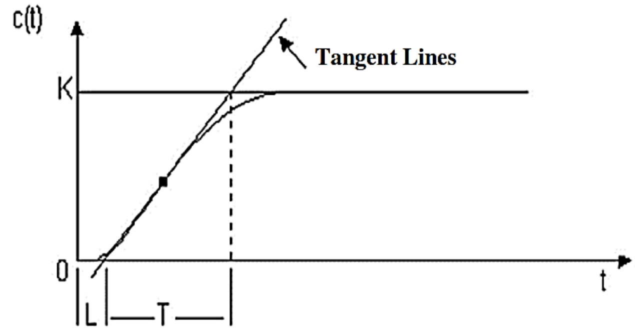


Figure 3. Curve response of the Ziegler-Nichols Method

The values of k, L, and T (where $a = kL/\ T$) can be determined through the straightforward estimation presented. By employing the variables L and a, one can derive the conditions of parameters utilizing the Ziegler-Nichols methodology.

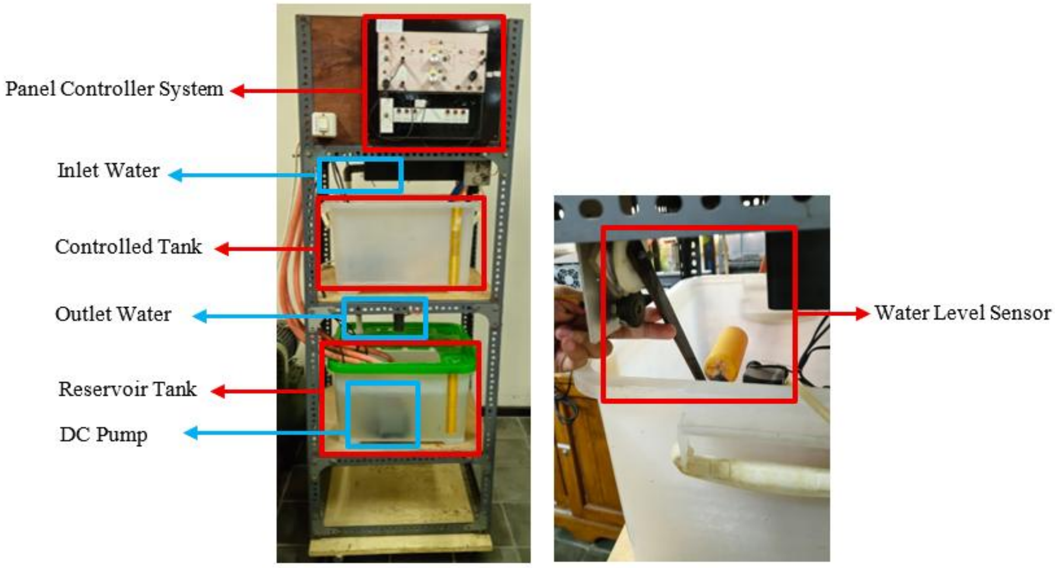
3 Material and Methods

Academic studies and research often use water-filling systems to test the structure of control systems. The system used for testing utilizes a tiered water-filling system, with one tank stacked on top of another. The upper tank serves as the control tank, and the lower tank serves as the reservoir. Figs 4(a) and (b) shows the setup and physical structure of the water-filling system used in this experiment.

The system has several parts of the hardware system attached to a plant:

- Water level sensor to measure the height of each tank
- DC pump that supplies water flow to fill a controlled tank system.

Figure 5 shows the controller panel equipped with a switch to activate the controller. The controller is set by changing the position of the selector to adjust the magnitude of the gain P, I, and D as shown in Figs. 6(a) - (c).



(a) (b)

Figure 4. The water tank; (a) physical arrangement of two tanks, (b) water level sensor

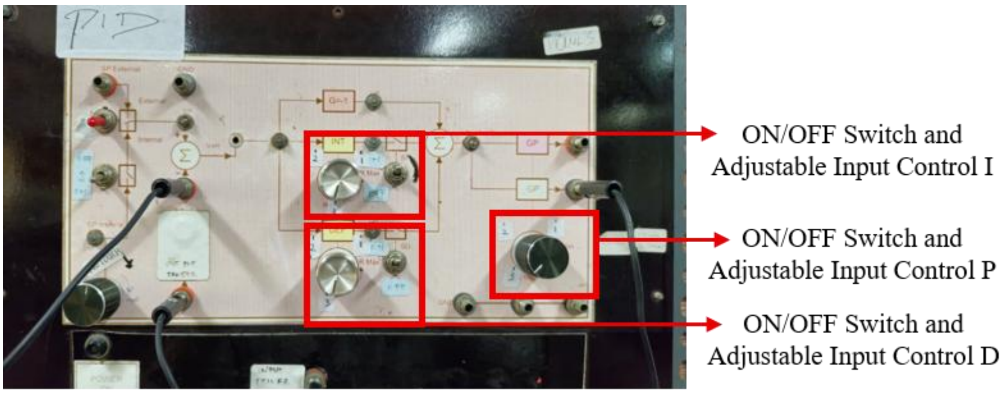
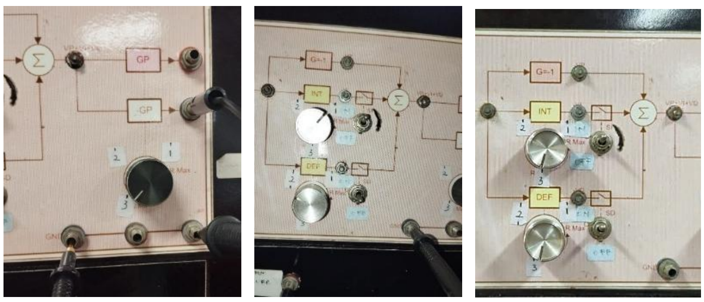


Figure 5. Panel Controller



(a) (b) (c)

Figure 6. Parameter controller setting; (a) Gain P in position 3, (b) Gain I in position 1, (c) Gain D in position 3

The research steps are as follows:

1. Collecting water level vs time data to model the plant
   Data collection was carried out using a multimeter and the water level in the control tank.
2. Manual tuning using the Heuristic method
   A. P action only
      a) Eliminate I and D
      b) Give step input, starting from K_p small, then increase it
      c) Find the best response and record the K_p value that provides the best response
   B. I action
      a) Eliminate D
      b) Use the K_p value obtained in step A
      c) Give step input, starting from a small K_i, then increase it
      d) Find the best response and record the K_i value that provides the best response
   C. D action
      a) Use the K_p value obtained in step A and the K_i value obtained in step B
      b) Give step input, starting from a small K_d, then increase it
      c) Find the best response and record the K_d value that provides the best response
3. Data collection was carried out using 9 position combinations.
4. Build a plant model
5. Design of PID controller
6. Simulation of water level control system

Heuristic data retrieval is taken as shown in Fig. 7. The set point value used in this study is 11.5 cm.

Figure 7. Data collection at the position P=3 and I=2

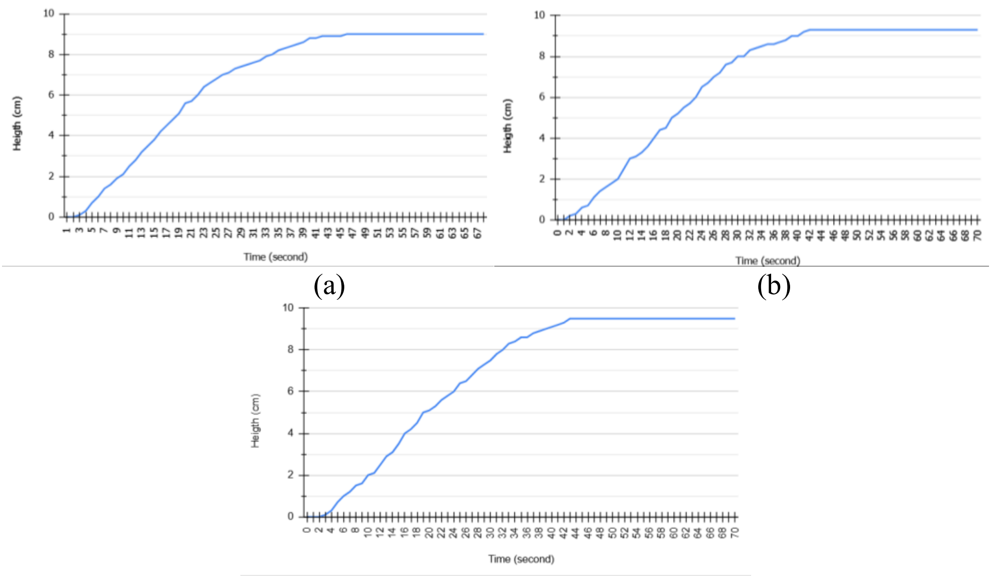
4 Results and Discussions

This research focuses on system analysis using a heuristic approach, modelling the system to design optimization of PID control using tuning with the Ziegler-Nichols method. The system used is a system that is not known to have a mathematical model or a Laplace form of the plant.

A. Heuristic Experiment

The results of the heuristic experiment for the P gain tuning of the system are shown in Figs 8(a) - (c). Transient Response with Proportional Controller shown in Table 2. Where τ = the time constant, T_r = Rise Time, T_s = Settling Time, FV = Final Value, and SSE = Steady State Error. The table shows that with a set point of 11.5 cm, the steady-state error (SSE) in all three experiments was still large, exceeding 17%, even with the K_p value increased. This indicates that using a proportional controller alone is insufficient for this water level control system. Therefore, an integral controller is necessary.

The results of the heuristic experiment for tuning the PI gain of the system are shown in Figs. 9(a) - (c). Transient Response of Plant with Proportional and Integrator (PI) Controller shown in Table 3. C_{max} is the highest value of the plant's response. In these three experiments, stability was not achieved, so the SSE value could not be calculated. However, when compared with the results of the P controller, the system output value was closer to the Set Point value (11.5 cm). Comparing the three figures, Figure 9(c) appears to have the best response, with the response oscillations decreasing rapidly. This means the system will reach stability more quickly. To achieve greater stability, the PI controller is combined with a derivative controller to form a PID controller.



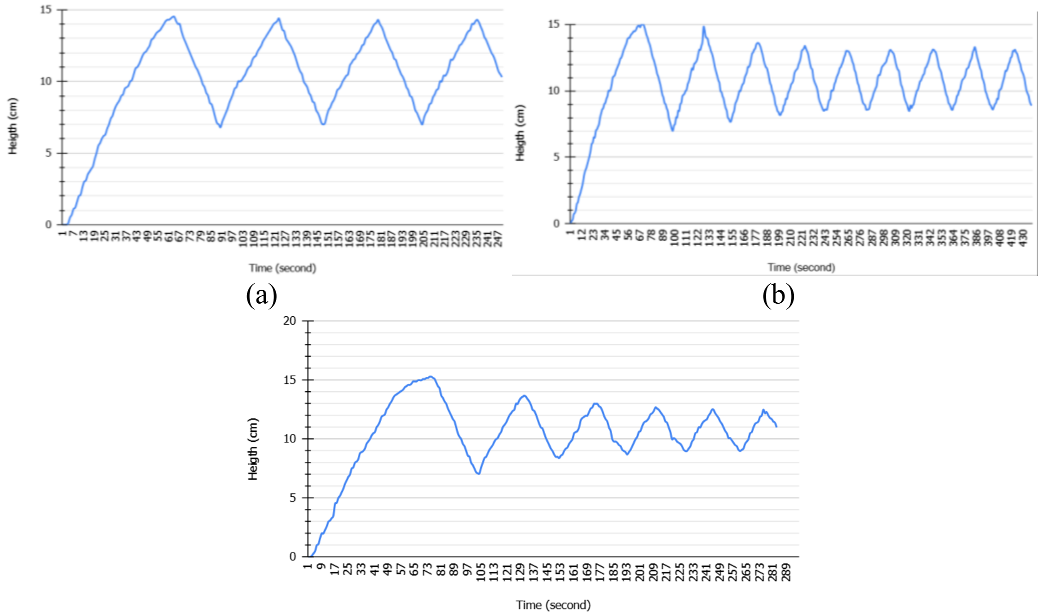
(a) (b)

(c)

Figure 8. Response with P; (a) Position 2, (b) Position 2.5, (c) Position 3

Table 2. Transient Response with P gain (K_p)

Experiment	Position	K_p	τ (s)	T_r (s)	T_s (s)	FV (cm)	SSE (%)
1	2	6.85	20	62.9	40	9	21.74
2	2.5	8.10	22.8	27.5	40.5	9.3	19.13
3	3	8.31	24	28.5	42	9.5	17.39



(c)

Figure 9. Response with PI; (a) in Position P=3, I=1, (b) in Position P=3, I=2, (c) in Position P=3, I=3

The results of the heuristic experiment for tuning the PID gain to the system are shown in Figure 10(a)(b)(c). Transient Response of Plant with Proportional Integral Derivative (PID) controller shown in Table 4. Figure 10 and Table 4 show that the best response was obtained in the third experiment with settings of K_P=8.31, K_i=4.75, and K_d=2.3. However, the results obtained were not as expected. Therefore, these results will be compared with the simulation results using MATLAB.

Table 3. Transient Response with PI

Experiment	Position		Gain		C_{max}	Tp (s)
	P	I	K_p	K_i		
1	3	1	8.31	9.57	14.5	64
2	3	2	8.31	7.30	15	68
3	3	3	8.31	4.47	15.3	19

Table 4. Transient Response with PID

Experiment	Position			Gain			C_{max}	Tp (s)
	P	I	D	K_p	K_i	K_d		
1	3	3	1	8.31	4.47	0.30	15.3	76
2	3	3	2	8.31	4.47	1.85	15.2	76
3	3	3	3	8.31	4.47	2.30	15.1	76

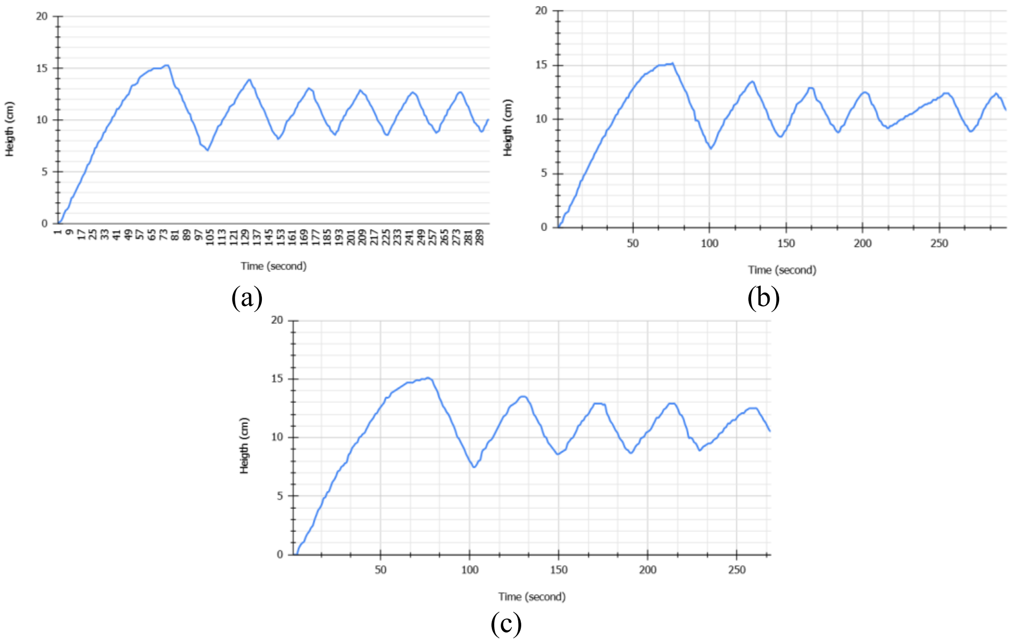


Figure 10. Response with PID in Position; (a) P=3, I=3,D=1, (b) P=3, I=3,D=2, (c) P=3, I=3, D=3

B. Numerical Simulation

i. Modelling

The plant used will be modeled by generating a response output from experimental results. The output of the open-loop system response is shown in Fig. 11. From an open-loop system based on experiment, the mathematical model of gain (K) is obtained, stated in equation (6).

$$K = \frac{\Delta C(s)}{\Delta M(s)} = \frac{13.3\ \text{cm}}{100\%\text{CO}} = 0.133\,\frac{\text{cm}}{\%\text{CO}} \qquad (6)$$

where CO = controller output.

The FOPTD model, as stated in Equation 2, with the Padé approximation as stated in Equation 3, can then be rewritten using Fit 1 (Fig. 12) and Fit 2 (Fig. 13). The data in this model is taken in an open-loop system.

From Fig. 12, the value is obtained $t_0 = 4s$ and $\tau = 39 - 4 = 35s$ so that the FOPDT model is stated in equation (7).

$$G_p(s) = \frac{0.133e^{-4s}}{35s+1} \tag{7}$$

Using Padé approximations, a plant model in Laplace's equation becomes equation (8).

$$G_p(s) = \frac{0.133}{35s+1}\ \frac{1-2s}{1+2s} \tag{8}$$

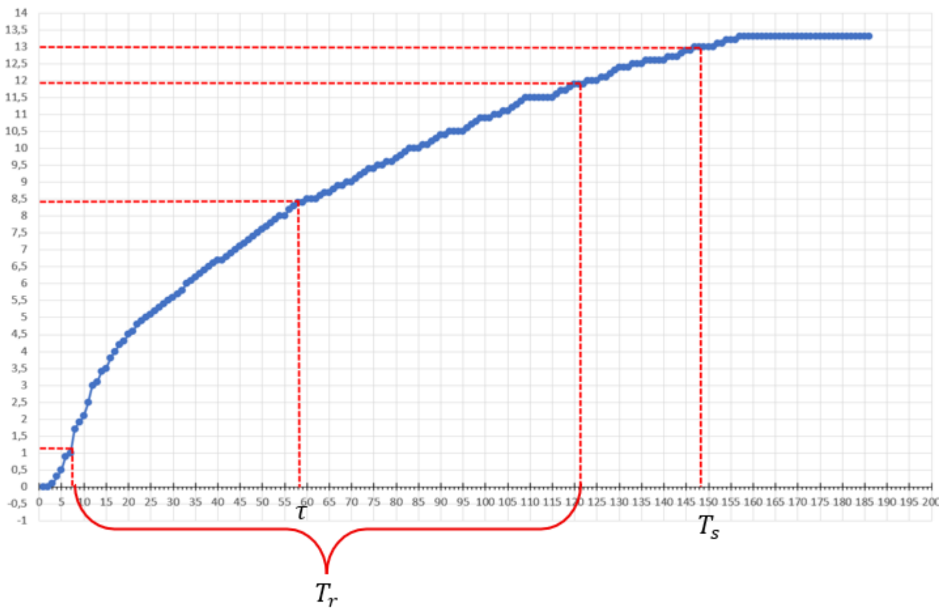


Figure 11. Response Open-loop Model

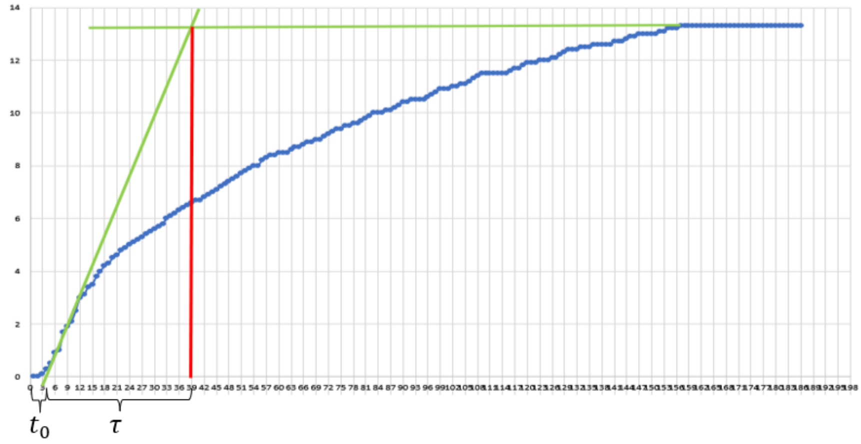


Figure 12. Open Loop Model using Fit 1

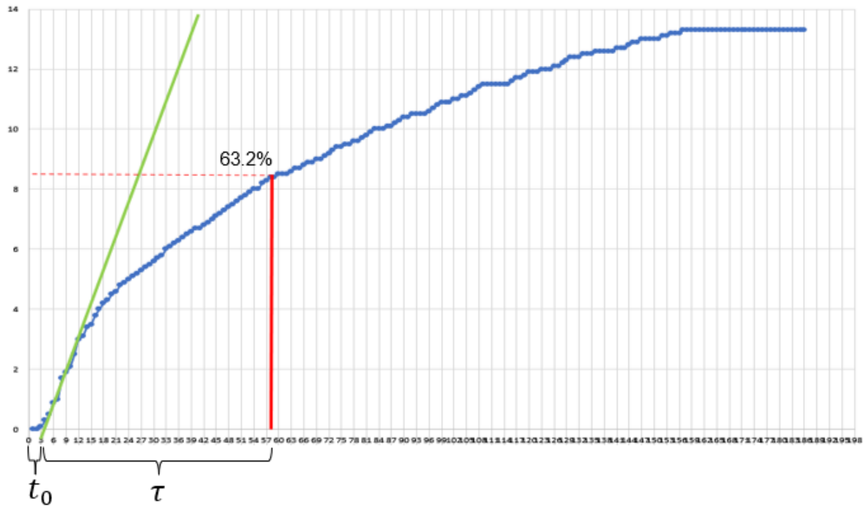


Figure 13. Open Loop Model using Fit 2

From Fig. 13, the value $t_0 = 4s$ and $\tau = 58 - 4 = 54s$ are obtained, so that the Laplace equation on the plant is stated in equation (9)

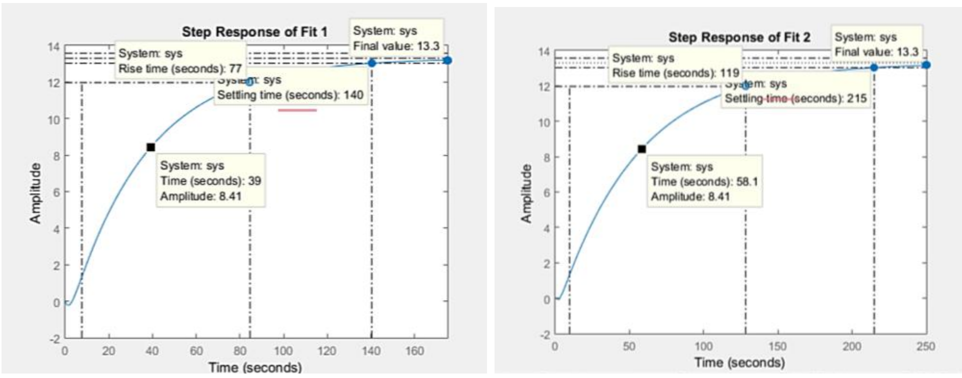
$$G_p(s) = \frac{0.133e^{-4s}}{54s+1} \tag{9}$$

Using Padé approximations, the plant equation in the Laplace model becomes equation (10).

$$G_p(s) = \frac{0.133}{54s+1} \frac{1-2s}{1+2s} \tag{10}$$

In the fit 3 modeling, t_1=15 seconds and t_2=58 seconds were obtained, which resulted in a negative dead time value, so the fit 3 modeling was not used.

For model comparison, the K value on the Fit 1 and Fit 2 models is multiplied by 100 to get the same Final Value as the actual value. The results of the simulation can be seen in Figs. 14(a) and (b). A comparison of the response characteristics between the model and the actual value is shown in Table 5. Considering that the settling time in the Fit 1 model is close to the actual value, the Fit 1 model is used in the next calculation.



(a) (b)

Figure 24. Simulation Result of the Modelling using; (a) Fit 1, (b) Fit 2

Table 5. Comparison Fit 1 and Fit 2

Parameter	Plant	Fit 1 Model	Fit 2 Model	Unit
Final Values	13.3	13.3	13.3	cm
Rise Time	114.8	77	119	second
Settling Time	147	140	215	second
Time Constant	58	39	58.1	second

ii. Controller Tuning using Ziegler-Nichols Method

Based on the Ziegler-Nichols rule, it produces the number of tuning results as shown in Table 6. In the table, 3 types of controllers are designed. They are Proportional (P), Proportional Integral (PI), and Proportional Integral Derivative (PID) controllers.

The amount of the controller gain will be used as a gain recommendation in the system. From the combination of gains, we will see the response of each gain in the system that has been modeled.

Proportional Controller (P Controller)

From Table 6, it can be obtained that $K_P = 8.75$. The block diagram of the system and the magnitude of the K_P gain are shown in Figure 15, and Figure 16 is the Transient Response of the system.

The model in Laplace's for the block diagram (Figure 15) is shown in equation (11).

$$\frac{C(s)}{R(s)} = \frac{8.75\,\frac{0.133}{35s+1}\,\frac{1-2s}{1+2s}}{1+8.75\,\frac{0.133}{35s+1}\,\frac{1-2s}{1+2s}} = \frac{-2.3275s+1.16375}{70s^2+34.6725s+2.16375} \quad (11)$$

The results of the simulation of the Laplace equation above are shown in Fig. 16.

Table 6. Controller Tuning using Ziegler-Nichols

Controller	K_p	T_i	T_d
P	8.75	-	-
PI	7.875	13.32	-
PID	10.5	8	2

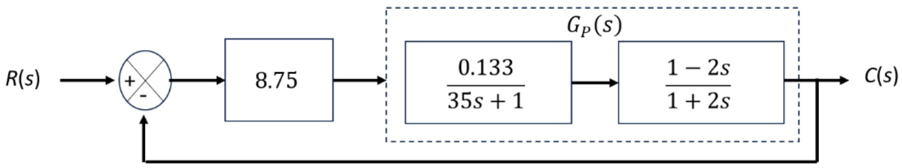


Figure 35. Ziegler-Nichols Tuning Block Diagram with $K_p = 8.75$

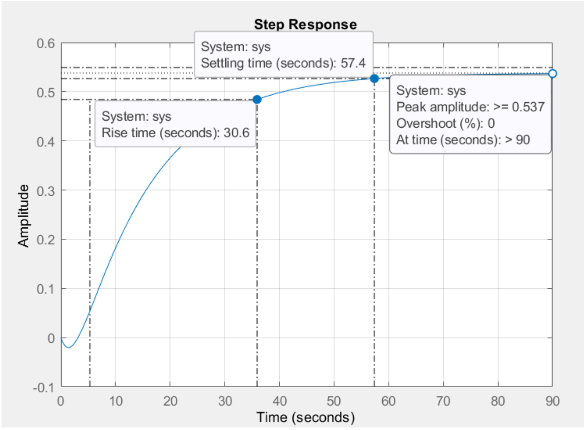


Figure 46. Response Transient using a Proportional controller only with K_p = 8.75

Proportional-Integral Controller (PI Controller)

From the table, it can be obtained that $\mathrm{K_p} = 7.875,\ \mathrm{T_i} = 13.32\mathrm{s}$. The value of Ki is shown in equation (12).

$$\mathrm{K_i} = \frac{1}{\mathrm{T_i}} = \frac{1}{13.32} = 0.0751 \tag{12}$$

The controller formula uses parallel structure, so the controller transfer function is shown in equation (13).

$$\mathrm{G_c(s)} = \mathrm{K_p} + \frac{\mathrm{K_i}}{\mathrm{s}} = 7.875 + \frac{0.0751}{\mathrm{s}} = \frac{7.875\mathrm{s}+0.0751}{\mathrm{s}} \tag{13}$$

The block diagram of the system with the magnitude of the $\mathrm{K_p}$ and $\mathrm{K_i}$ gain is shown in Fig. 17. The transfer function of the system is stated in equation (14).

$$\frac{\mathrm{C(s)}}{\mathrm{R(s)}} = \frac{\frac{7.875\mathrm{s}+0.0751}{\mathrm{s}}\ \frac{0.133}{35\mathrm{s}+1}\ \frac{1-2\mathrm{s}}{1+2\mathrm{s}}}{1+\frac{7.875\mathrm{s}+0.0751}{\mathrm{s}}\ \frac{0.133}{35\mathrm{s}+1}\ \frac{1-2\mathrm{s}}{1+2\mathrm{s}}} = \frac{-2.0948\mathrm{s}^2+1.0274\mathrm{s}+0.01}{70\mathrm{s}^3+34.9052\mathrm{s}^2+2.0274\mathrm{s}+0.01} \tag{14}$$

The results of the simulation of the Laplace equation above are shown in Fig. 18.

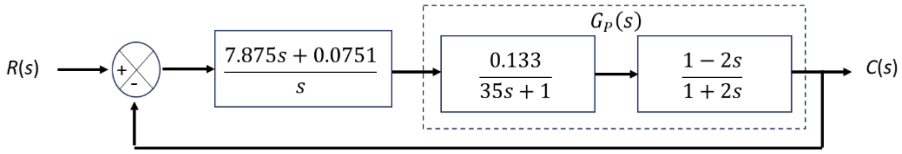


Figure 5. Ziegler-Nichols Tuning Block Diagram with $K_p = 7.875$ *and* $K_i = 0.0751$

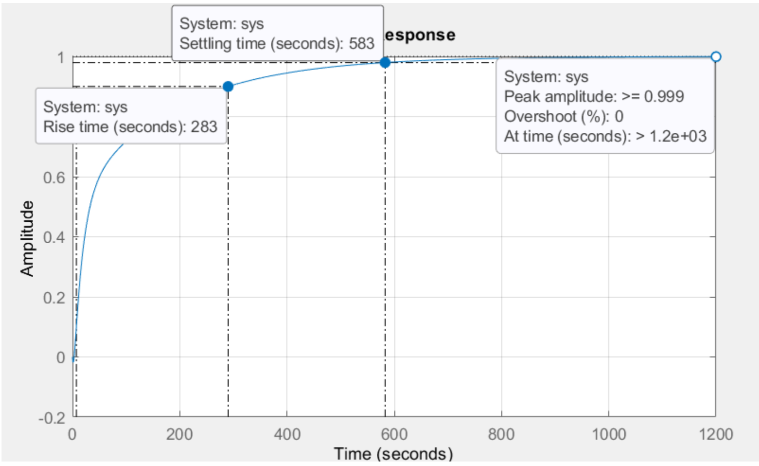


Figure 18. Response Transient using PI controller with K_p = 7.875 and K_i=0.0751

Proportional-Integral-Derivative Controller (PID Controller)

From Table 6, it can be obtained that $K_p = 10.5$, $T_i = 8s$. The values of K_i and K_d are stated in equations (15) and (16).

$$K_i = \frac{1}{T_i} = \frac{1}{8} = 0.125 \tag{15}$$

$$K_d = T_d = 2 \tag{16}$$

The controller formula uses parallel structure, so the controller transfer function is shown in equation (17).

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s = 10.5 + \frac{0.125}{s} + 2s = \frac{2s^2+10.5s+0.125}{s} \tag{17}$$

The block diagram of the system and the magnitude of the K_p, K_i, K_d gains are shown in Fig. 19. The transfer function of the system is stated in equation (18). Fig. 20 shows the Transient Response of the system.

A comparison of these three curves is presented in Fig. 21 and Table 7. This figure and table compare the transient response of the system with P, PI, and PID control mechanisms. All three systems were given step input. In the first simulation, the plant was controlled using only a P controller with a Kp value of 8.75. It appears that the system has the fastest rise time value, which requires approximately 30.6 seconds.

$$\frac{C(s)}{R(s)} = \frac{\frac{2s^2+10.5s+0.125}{s}\,\frac{0.133}{35s+1}\,\frac{1-2s}{1+2s}}{1+\frac{2s^2+10.5s+0.125}{s}\,\frac{0.133}{35s+1}\,\frac{1-2s}{1+2s}}$$

$$\frac{C(s)}{R(s)} = \frac{-0.532s^3-2.527s^2+1.3633s+0.0166}{69.468s^3+34.473s^2+2.3633s+0.0166} \tag{18}$$

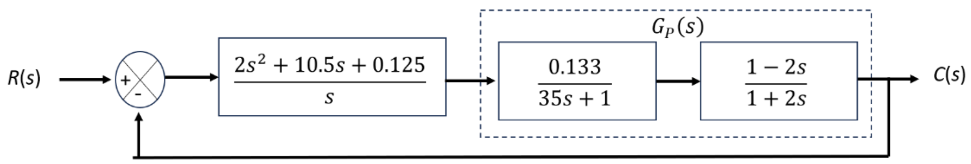


Figure 19. Ziegler-Nichols Tuning Block Diagram with $K_p = 10.5\,, K_i = 0.125\ and\ K_d = 2$

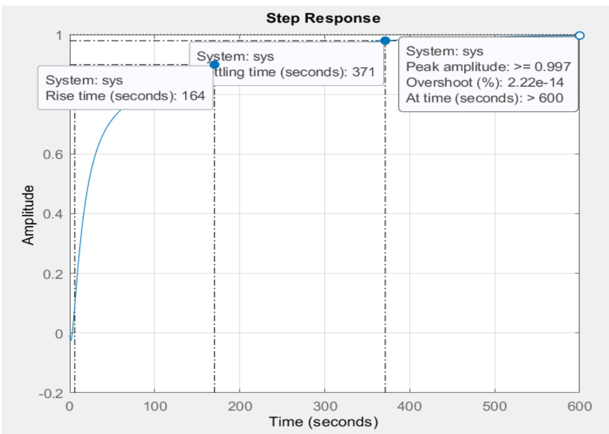


Figure 206. Response Transient use PID controller with K_p=10.5, K_i= 0.125 and K_d= 2

However, the Final Value in this system is 0.538. This means the system cannot achieve the desired value with an SSE of 46.2%. The P controller alone is not sufficient to control the water level. Therefore, it is necessary to add an integral controller so that the plant is controlled with a PI controller. In the second experiment with the addition of a P controller of 7.875 and an I controller of 0.075, the system response is quite good, where the system has a Final Value of 1 with zero steady-state error. However, in this experiment, the settling time is long, namely 583 seconds, with a rise time of 283 seconds. To speed up the response, a derivative controller is added. The third experiment, where the plant was controlled with a PID controller, had a Final Value of 1 with a shorter settling time and rise time compared to the second experiment, although there was a very small overshoot.

From the results of PID modeling and tuning using Ziegler-Nichols, it was found that the control system with a PID controller was the best choice, with a configuration of K_p = 10, K_i = 0.125, and K_d = 2. The system with a PID controller can achieve a Final Value of 1 with the fastest rise time and the fastest settling time. When compared with the tuning results using the heuristic method with maximum gain settings (K_p = 8.31, K_i = 4.75, and K_d = 2.3), the K_p gain needs to be increased, while the K_i gain needs to be decreased. Because the K_p gain is directly proportional to the resistance value, while the K_i gain is inversely proportional to the value, the resistance value for both gains must be increased.

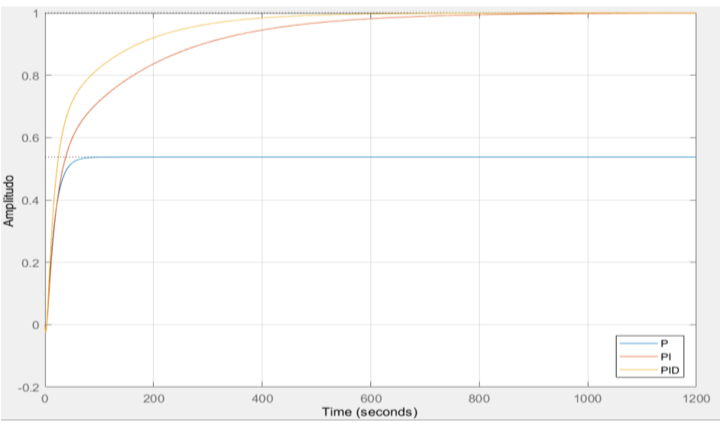


Figure 21. Comparison of Response Transient with Ziegler-Nichols

Table 7. Response Transient

Experiment	K_p	K_i	K_d	T_s (s)	T_p (s)	FV	T_r (s)	%OS	SSE (%)
1	8.75	-	-	57.4	-	0.538	30.6	0%	46.2
2	7.875	0.0751	-	583	-	1	283	0%	0
3	10.5	0.125	2	371	>600	1	164	2.22e-14 %	0

5 Conclusions

The water tank system testing was carried out by observing the performance of the addition of P, PI, and PID controllers to the water level in the tank using a heuristic method compared with the tuning results using Ziegler-Nichols. From the results of the plant simulation with the Fit 1 model, the best controller value for the system that can effectively improve the level control performance is the PID controller with a value of K_p= 10, K_i= 0.125, and K_d = 2. Tuning using the Ziegler-Nichols method produced a good response, where the final value of the water level was the same as the set point value (SSE = 0%) with a settling time of 371 seconds (6.18 minutes). Heuristic tuning for the plant used in this study failed to achieve the setpoint value due to limitations in the available controllers. For the system to work optimally, the resistance values K_p and K_i need to be increased.

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