

Development of a low-cost PID tuning kit for engineering education

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ABSTRACT

PID controller is used in roughly 90% of process control plants in the industry to deliver better performance to process plants. The PID controller tuning requires adequate knowledge and a deep understanding of the controller. Nevertheless, tuning a PID controller is difficult; if it is poorly tuned, the process plant will face diminishment in terms of performance. To overcome this problem, educational institutions ought to train and offer enough knowledge and understanding of PID tuning to meet industry requirements. However, most institutes can only provide minimal expertise due to a lack of facilities for experimenting with PID controller tuning. This is because the PID trainer kit in the current market is very pricey. Therefore, this study aims to develop a low-cost PID trainer kit for students. The main objective of this project is to make improvements to the design and system of the PID tuning kit that already exists. This PID tuning kit system is developed using Arduino Mega 2560 and LabVIEW. In this project, Arduino acts as a microcontroller for the PID control system, and LabVIEW is used as a data logger to display the output response. Three knobs of potentiometer are utilized to manipulate the parameter of gain in the PID controller. The result from this project is the output response for the P, I and D controller and its combination. The gain value input from the controller influences the output response. The output response is proportional to the error and gain value for the P controller. For the I controller, the output response is proportional to the integral magnitude and error to time. For the D controller, the output response is proportional to error rate changes over time. To conclude, this PID trainer kit can simulate the tuning process of an actual PID controller in the industry.

1. Introduction

The Proportional-Integral-Derivative (PID) controller is used in an automatic control system to control the process variables such as temperature, level, flow, pressure and pH value. The PID controller is widely used in the industrial control field due to its simplicity, good stability and high accuracy[1]–[4]. The PID controller provides three control methods based on Proportional (P), Integral (I), and Differential (D) parameters. The control parameters require good tuning to provide

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a good output response. Therefore, they must be tuned correctly to ensure that a PID controller works properly, which leads to increased process control performance in the industry[5]–[9].

Tuning the PID controller will be a tough and troublesome task if the person or operator does not understand the fundamental concept of PID tuning. To tackle this problem, an organization or company must invest a lot of money to provide adequate training to their employees to enhance their knowledge and skills in tuning PID controllers[10]–[14]. Hence, this study focuses on developing and applying the PID tuning trainer kit. This study aims to develop a trainer kit that can enhance comprehension of the concept of tuning the PID controller. This trainer kit can be used during teaching and learning sessions since it is compact in design, safe to handle and can improve skills by providing hands-on experience tuning the PID controller. Currently, various tuning methods are used in various industries[15]–[17]. This study will differentiate each tuning method to determine the most suitable application in the industry.

2. Methodology

2.1 The control system

The PID controller is widely used in industrial control systems. It is shown in Eq. (1) to define the input to the controller, $u(t)$.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (1)$$

K_p , K_i and K_d are proportional, integral and derivative coefficients, respectively. $e(t)$ is the difference between the reference and the output value, which becomes the input of the PID controller.

Figure 1 shows the block diagram for the PID tuning kit for the water level control system, which is based on a closed-loop system. In this control system, the manipulated variables are the water pump and the solenoid valve, and the control value/process value is the water level. The ultrasonic sensor measures the water level inside the tank. The current value is then compared with the setpoint value to get the differences or the error. Then, the water pump and the solenoid valve are manipulated based on the value given by the PID controller.

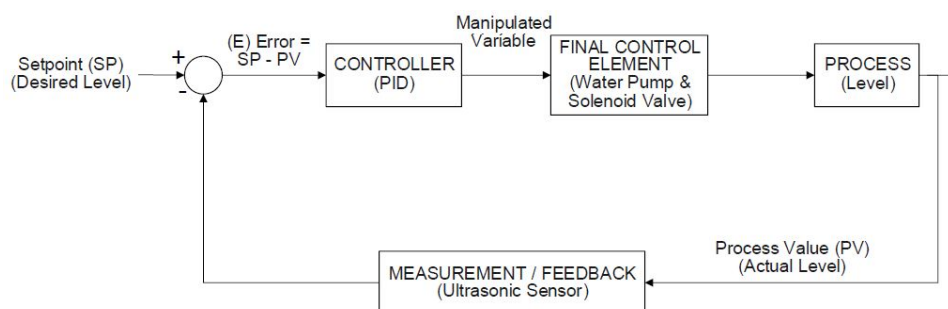


Fig. 1. The block diagram of the water level control system

2.2 The process flowchart

Figure 2 shows the flowchart for the water level system PID tuning kit. The flow process starts when the power button is turned on. First, the kit initializes the set-point (SP) level, 9 cm for the maximum level. After that, it reads the process value from the ultrasonic sensor. Then, the PID controller calculates the error by comparing the set point with the process value. Afterwards, it acquires the gain value for the P, I and D controllers from the potentiometer knob. The user inserts this value. The P gain must be greater than zero, while the I and D gain values must be equal to or

greater than zero. Next, P, I and D control action output is calculated based on the gain value from the potentiometer.

After that, the system calculates the water level and detects whether the setpoint has been achieved. If the setpoint has been reached, the water pump is turned on, and at the same time, the solenoid valve is turned off, and vice versa if the setpoint is not achieved. Then, the output response of the PID tuning kit is shown on the LABVIEW software and exported to Microsoft Excel.

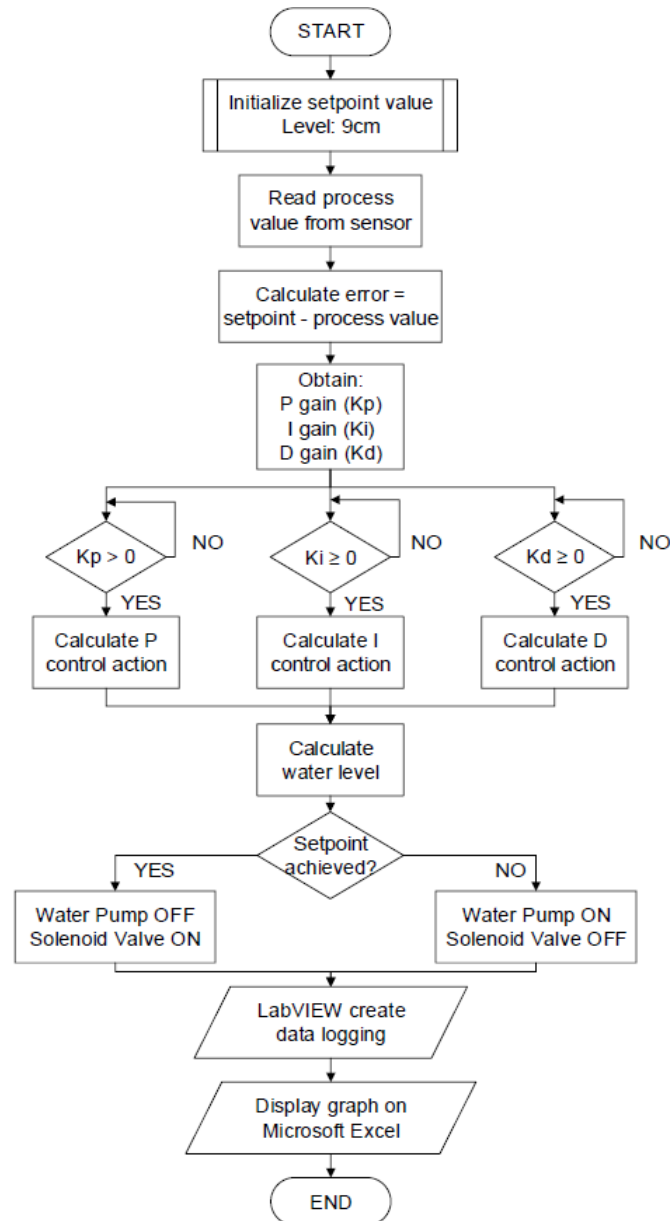


Fig. 2. The flowchart of the water level control system PID tuning kit.

2.3 The prototype design and development

Figure 3 shows the circuit diagram of the system. This project uses an Arduino Mega 2560 as the microcontroller, potentiometer, ultrasonic sensor, relay module, solenoid valve, and water pump. Three potentiometers are used as a control knob to change the gain value for P, I, and D, respectively.

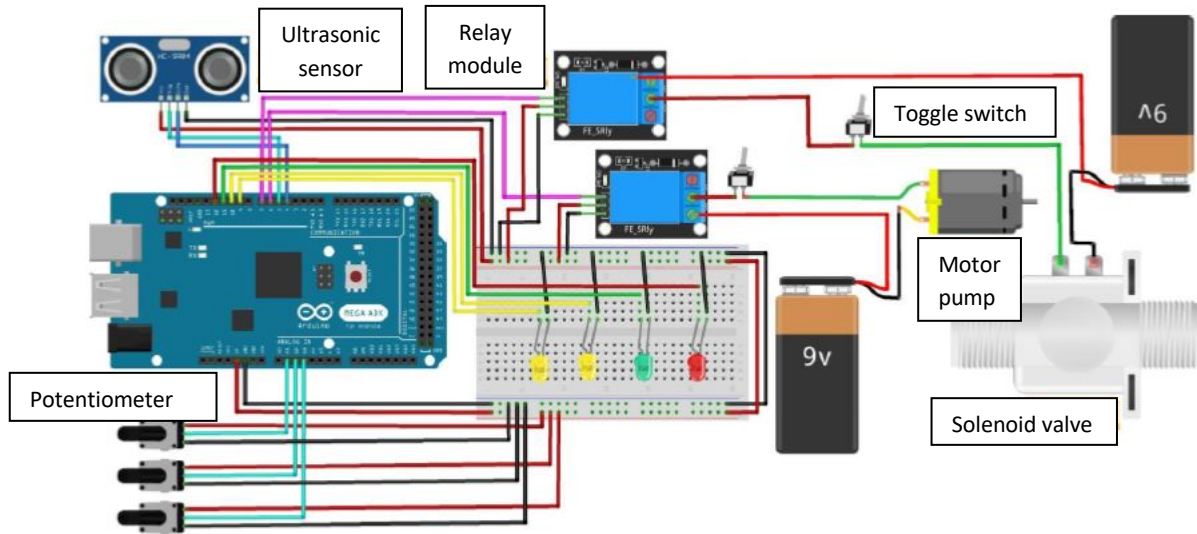


Fig. 3. The circuit diagram of the water level control system PID tuning kit

The knobs can be used separately or in combination to form P, PI, PD, and PID controllers. For instance, if the control system only requires a P controller, the I and D gain values can be set to zero. The potentiometers are connected to an analog input of the Arduino microcontroller board. Then, the output response will be generated based on the gain value inserted by the user. The ultrasonic sensor is connected to the digital pin of the Arduino Mega 2560 and is used as a feedback element in the control system.

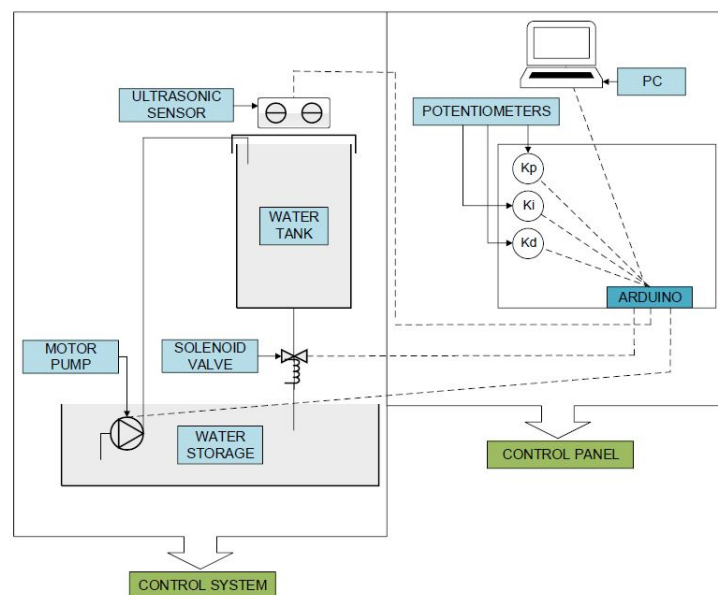
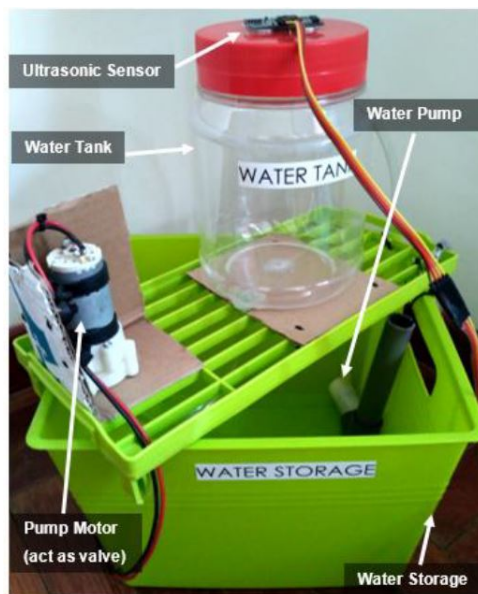


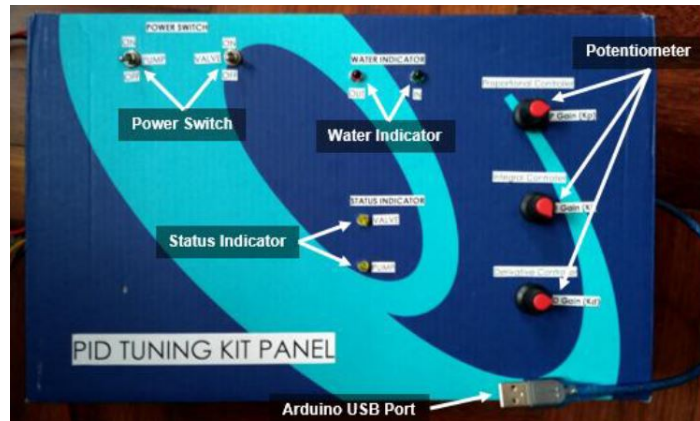
Fig. 4. The diagram of the water level control system PID tuning kit

Next, the solenoid valve and water pump are connected to the relay module, which controls the output response from both. Finally, LabVIEW is connected to the Arduino using USB so that the output response can be displayed on LabVIEW and monitored by the user. The prototype consists of two parts, as shown in Figure 4: a control panel (developed using LabView software) and hardware development for the water level control system. Figure 5 shows the water level control system PID tuning kit prototype. The prototype comprises the water level control system and the PID tuning kit

box. Figure 5(a) is the water level control system in which the solenoid valve was replaced with the water pump to increase the water flow. Figure 5(b) is the main component of this project, which is the programmable controller of the PID tuning system.



(a) The water level control system



(b) PID tuning kit panel

Fig. 5. The picture of the water level control system PID tuning kit

2.4 The LabVIEW front panel

Figure 6 shows the front panel of LabVIEW for this project[18]–[20]. It consists of various controls and indicators, such as a vertical fill slide, waveform chart, stop button, LED indicator, and current time indicator. The system starts with system initialization before running the system. When the system is started, it will read the analogue input value entered by the user and convert it to a digital signal. Then, the ultrasonic sensor reads the water level distance in the tank. If the water level distance from the sensor is more than 6 cm, it triggers the pump to be turned on; otherwise, vice versa. After that, all the data from the experiment are logged into Microsoft Excel for further analysis.

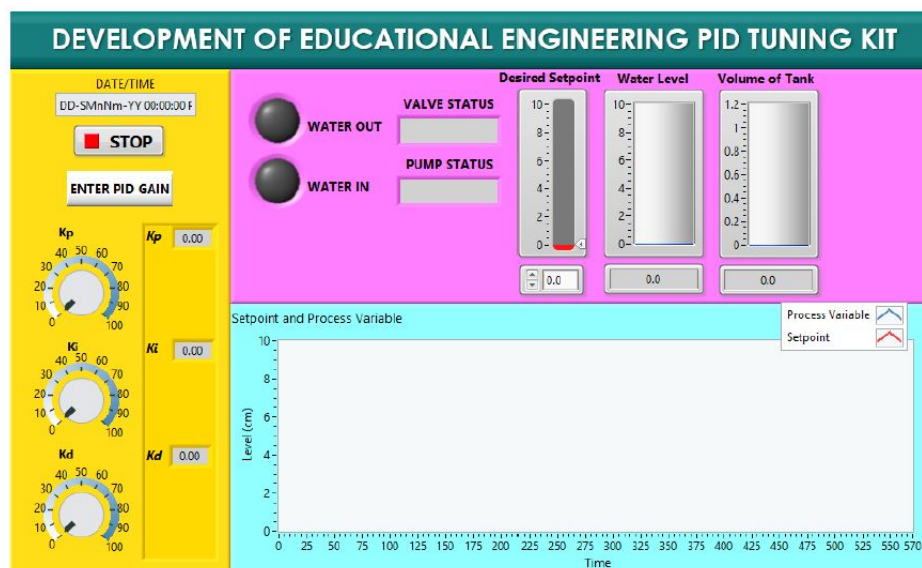


Fig. 6. The front panel of the LabVIEW

2.5 The experiment

The experiment was conducted to test the system's performance by tuning the PID controller using Ziegler-Nichols (ZN) and Tyreus-Luen (TL) tuning methods. The critical gain, K_c , and the oscillation period, T_c , must be obtained using the closed loop P control test. Both values can be obtained by adjusting the proportional gain until the output response reaches periodic oscillation. The critical gain, K_c , is the proportional gain, K_p , when the output oscillates. The oscillation period, T_c , is the time between two peaks of the output response. Finally, the gain K_p , K_i and K_d are calculated using ZN and TL tuning rules.

1.2 L of water was inserted into the water storage container. Then, the Arduino board was connected to the PC, and the LabVIEW program was uploaded to the Arduino board. On the LabVIEW front panel, click the RUN button. Within 30 seconds, the gain value for the proportional controller was set at 5 by adjusting the potentiometer. The pump and the solenoid valve opening and closing are turned on simultaneously. Increase the proportional gain value by 5 until the output response sustains periodic oscillation. After getting a periodic oscillation of the output response curve, the proportional gain of the controller is recorded as the critical gain, K_c . Next, the oscillation duration was found between two peaks and recorded as an oscillation period, T_c .

3. Results and discussion

3.1 The closed loop P control test.

The PID critical gain, K_c , also known as the ultimate gain, is the marginal gain, a point of non-return. It is the gain where the system starts to oscillate, where $K_c = K_p$. The oscillation period, T_c , is the process variable oscillation pattern period at the critical gain or time between two peaks.

Figure 7 shows the water level's output response when the proportional controller gain is set at 20, and the output response oscillates. Thus, the process's critical gain is 20, and the oscillation period is 10 seconds.

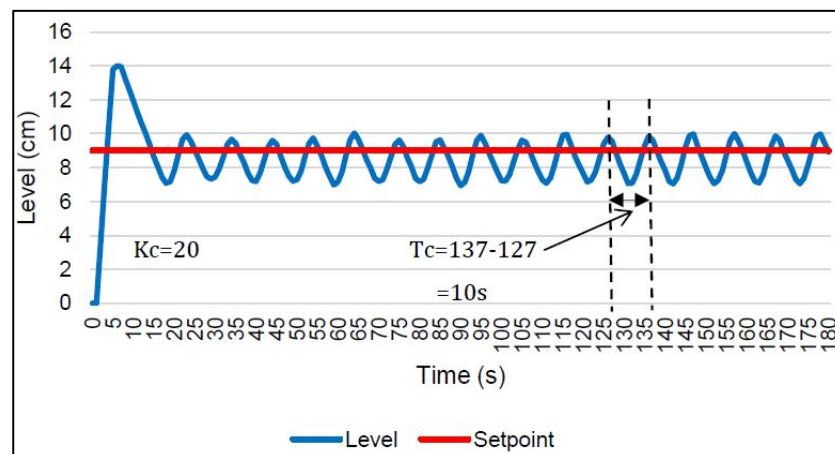


Fig. 7. The output response curve for $K_p = 20$

3.2 The Ziegler Nichols tuning method

Table 1 shows the PID tuning results using the ZN method[7], [21]. The integral time, T_i and the derivative time, T_d were used to find the K_i and K_d values. From Table 2, T_i was converted into K_i using Eq. (1), and for the T_d , it was converted into K_d using Eq. (2).

$$K_i = \frac{K_c}{T_i} \quad (1)$$

$$K_d = K_c \times T_d \quad (2)$$

Table 1

The ZN tuning result

Controller type	K_p	T_i	T_d
P	$0.5 \times 20 = 10$	N/A	N/A
PI	$0.45 \times 20 = 9$	$10/1.2 = 8.33$	N/A
PID	$0.60 \times 20 = 12$	$0.5 \times 10 = 5$	$10/8 = 1.25$

Table 2

The ZN tuning results after conversion

Controller type	K_p	K_i	K_d
P	10	N/A	N/A
PI	9	$9/8.33 = 1.08$	N/A
PID	12	$12/5 = 2.4$	$12 \times 1.25 = 15$

Then, the experiment was conducted for each type of controller, P, PI, and PID, based on the gain value in Table 2 to investigate the process's output response after controller tuning using the ZN method. The results are shown in Figure 8. Figure 8(a) shows the output response of the P controller. The water level rises rapidly towards the set point, 9 cm, causing an overshoot of 11.7 cm. After that, the water level drops below the set point and reaches a steady state, with a settling time of 60 seconds.

Figure 8(b) shows the PI controller's output response. The results show that the water level overshoot at 12.5 cm before it reached the steady state at 70 seconds. The water level can achieve the set point, which proves that the integral gain can eliminate the offset within the system. Figure 8(c) shows the output response using the PID controller. The water level rises instantly in less than 5 seconds and overshoots about 10 cm from the setpoint. Although this output response has the shortest rise time, the process does not achieve a steady state and continuously oscillates without reaching the set point. Thus, the derivate gain is not suitable to use for level control.

Based on the results of the three types of controllers, the P controller has more stability than the PID controller despite not achieving the set point. This is due to a large shortcoming when using the P controller alone, which leads to a residual sustained error called offset. As a result, the error remains constant, causing the system to hold its position below the set point value. Furthermore, the P controller generates the lowest overshoot compared to the PI and PID controller. Although the PI controller has the highest overshoot and longest rise time among the three controllers, it can achieve a steady state at the set point. Therefore, based on the ZN tuning method, the PI controller is the most suitable controller type for the water level process as it manages to achieve the set point level, attain the steady state and produce the most stable output response.

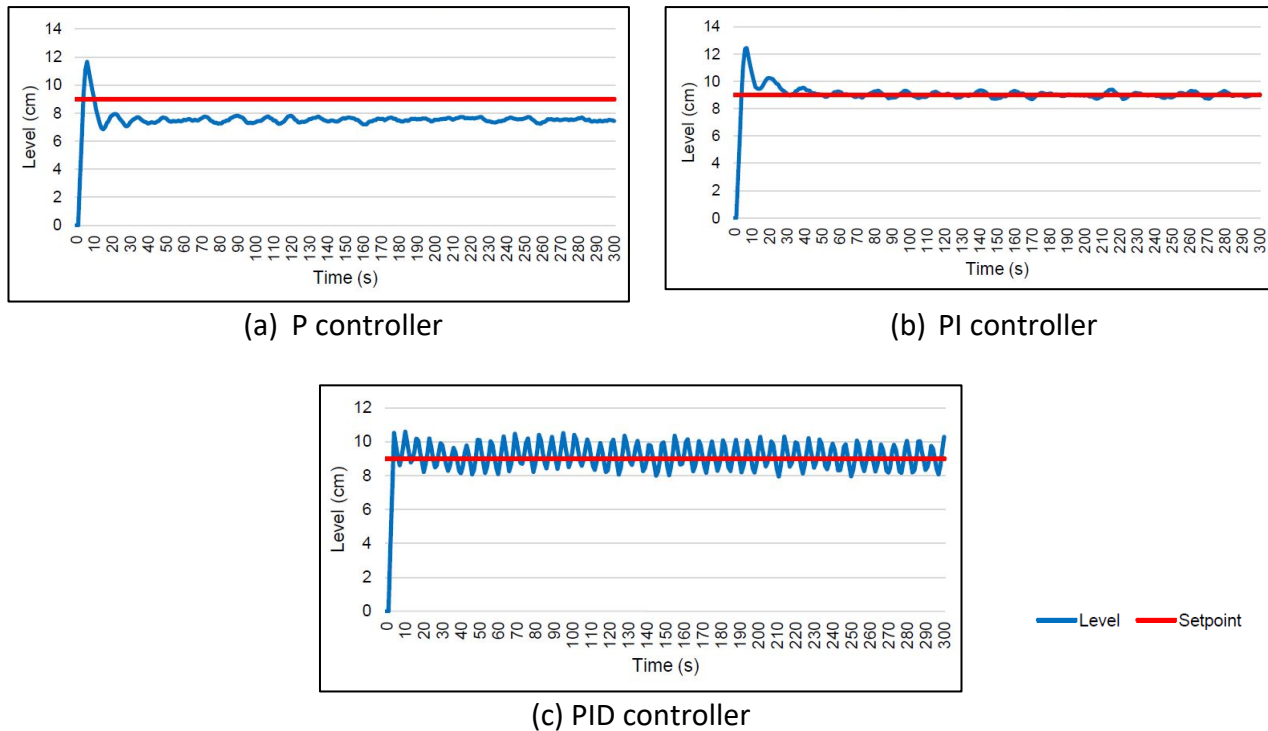


Fig. 8. The output response using the ZN tuning method

3.3 The Tyreus-Luben tuning method

Tables 3 and 4 show the results of parameter calculation using the Tyreus-Luben tuning method[2], [18]. The T_i and T_d values must be used to find the K_i and K_d values. The experiment used the values in Table 3 for the PI and PID controller to obtain the output response using the TL tuning method.

Table 3

The TL tuning result

Controller type	K_p	T_i	T_d
PI	$20/3.2 = 6.25$	$2.2 \times 10 = 22$	N/A
PID	$20/3.2 = 6.25$	$2.2 \times 10 = 22$	$10/6.3 = 1.59$

Table 4

The TL tuning results after conversion

Controller type	K_p	K_i	K_d
PI	6.25	$6.25/22 = 0.28$	N/A
PID	6.25	$6.25/22 = 0.28$	$6.25 \times 1.59 = 9.94$

Figure 9 shows the results of the PI and PID controller experiment using the TL tuning method. Based on Figure 9 (a), the water level went up steeply towards the setpoint, but there was a drop in the first 20 seconds. Afterwards, the water level gradually increased again to the set point. However, the water level only reached the setpoint at 130 seconds, and then it reached a steady state. Figure 9(b) shows the output response for the PID controller. The water level rises moderately with some oscillation, and the rise time is 25 seconds. Then, it started to oscillate and did not reach the set point.

When the output response for the PI and PID controllers is compared, the PI controller produces a longer rise time but a better settling time. In addition, it can reach the desired set point before it attains a steady state and stability. However, the PID controller continuously oscillates and remains

unstable. Thus, the PI controller performs better than the PID controller for the TL tuning method since it can achieve the set point value despite the longer rise time.

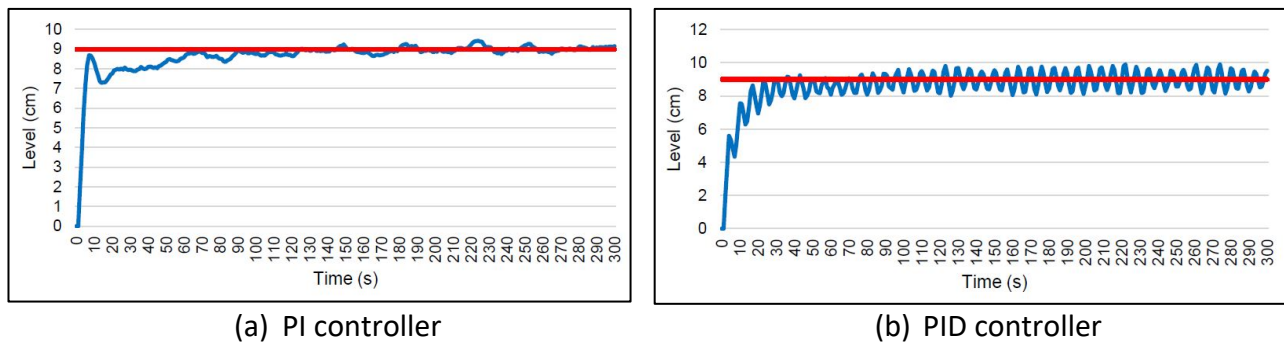


Fig. 9. The output response using the TL tuning method

4. Conclusions

An experiment was conducted using a PID tuning kit to control the water level system. The controller used ZN and TL tuning methods to tune the P, PI, and PID controllers. Based on the output response, the PI controller that had been tuned using the ZN tuning method generated a shorter rise time and quicker settling time than the PI controller that was tuned using the TL tuning method, although it had an overshoot. This is because the goal of control system implementation is not to eliminate error, as it is impossible to eliminate the errors in the control system. Yet, it can be minimized without affecting the overall system performance and stability.

In conclusion, the water level system PID tuning kit was developed using the Arduino Mega 2560, which simulated the PID control system based on the experiment results. The kit offers a simulation of a real-life condition for PID controller tuning in the water level application. Through this simulation, the student can envisage tuning the controller to achieve a desired point. Using the prototype of the project, the output behaviour of the P, I and D controllers and their combination can be observed and analysed through a hands-on experiment. For future recommendations, the PID tuning kit can be used in actual teaching and learning sessions, and feedback from the students in terms of application efficiency can be obtained to understand the theory with practical sessions.

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