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The Effects of P, I and D Parameters in Automatic Liquid Level Control Using UniTrain Module

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***Abstract*—The research discusses some experiments to control the level of liquid inside a tank by using PID controllers which can be divided into four categories. The experiments describe the effect of P, I, and D element. It also discusses the best possible controller, which is a PI controller, for the liquid level tank system. The liquid level controlling is done by adjusting the voltage pump which will further regulate the flow rate of the fluid entering the inlet valve. The liquid that flows through the outlet valve is considered as the disturbance variable to the system. The liquid tank sensor needs to be calibrated prior to the experiments. Calibration can be done manually by using a digital multimeter or by using the computer sofware that is connected directly to the plant system. Set point and PID parameters are determined by the UniTrain and the computer interface. In these experiments, PI controller has the best result with a medium proportional gain (K_P = 5) and a small integral gain (T_N = 0.2).**

Keywords: ***liquid level control, UniTrain, PID controller, automatic control***

***Abstrak*—Penelitian ini membahas beberapa eksperimen untuk mengontrol tinggi permukaan cairan dalam tangki secara otomatis dengan menggunakan pengendali PID. Eksperimen ini secara umum dapat dibagi dalam empat kategori. Penelitian ini menjelaskan pengaruh Parameter P, I, dan D dalam pengendali PID. Penelitian ini juga akan membahas bentuk pengendali PID yang tepat untuk mengendalikan tinggi permukaan cairan dalam tangki (PI kontroler). Pengendalian tinggi permukaan cairan dilakukan dengan mengatur tegangan pompa yang selanjutnya akan mengatur laju aliran cairan melewati katup masukan. Cairan yang keluar melalui katup pembuangan dianggap sebagai variabel gangguan pada sistem. Sensor tangki cairan perlu dikalibrasi terlebih dahulu. Kalibrasi dapat dilakukan secara manual dengan menggunakan multimeter digital atau dengan menggunakan komputer yang terhubung langsung pada sistem miniatur tangki. Reference point dan parameter-parameter PID dapat diatur menggunakan UniTrain dan komputer. Dalam penelitian ini, PI kontroler memiliki hasil yang terbaik dengan nilai penguat proporsional yang sedang (K_P = 5) dan nilai penguat integral yang kecil (T_N = 0,2).**

Kata kunci: ***pengaturan otomatis, pengendali PID, UniTrain, tinggi permukaan***

I. Introduction

In early 2012, several new equipments were granted for the control systems laboratory in order to support basic courses in Electrical Engineering Department, Faculty of Engineering, Syiah Kuala University. One of the equipments is a liquid level control system. It is a miniature version of a liquid tank which is widely used in industrial process. The miniature tank is connected to UniTrain unit as the control system and a computer is used as an interface to plot the response. To learn about the system, some experiments need to be conducted in order to improve the knowledge and the experience related to industrial process control.

The implementation of this experiment is useful for designing PID controller on a tank that contains liquid. According to Günes and Uraz, the liquid level control system is very widely used in industrial applications, especially in chemical and food processing, as well as in petroleum related industries [1]. Typically, there is always liquid level control in one of the loops that needs to be controlled in a process control system. This loop can be either single or multi-level control loop [2].

It cannot be denied, even if the PID controller is one of the oldest controller ever applied in the control systems, this type of controller is still the most favourite choice. PID popularity is based on the simplicity of the architecture itself and the easiness of tuning/setting the PID parameters.

PID has been implemented in the industry long before the development of the digital age (computer), which is around the 1930's, during which the PID controller is implemented using analog electronic circuits and even many of them are built using purely mechanical and pneumatic components [3].

A part from investigating the effect of each gain and designing a PID controller which will obtain the best possible result, this research is also looking at the effect of proportional, integral and derivative gains/elements in relation to noises within the system and as well as the system behaviour.

II. Background

A. PID Controller

PID stands for Proportional, Integral, and Derivative. The most common controllers found in liquid level control system are PID controllers. Figure 1 shows the general form of the controller, where the error signal e(s) is the input controller and actuator signals U(s) is the controller output [4]. K_P, K_I and K_D are respectively proportional, integral and derivative gain.

PID parameters need tuning first. The process of tuning is done to obtain the optimal values of the parameters. One method of tuning PID, which is frequently used, is Zieger-Nichols method. This method was first introduced in a journal published in 1942 by J.G. Ziegler and N.B. Nichols, both of whom worked for the Taylor Instrument Companies in Rochester, New York [5]. Modern PID tuning methods are based on fuzzy logic [6, 7] and the combination of neural network with fuzzy logic, better known as neuro-fuzzy [8]. PID can also be tuned by using genetic algorithms. However, the simplest way of tuning PID parameters is by trial and error method.

PID controller is the oldest controller ever used in the control system. Although innumerable research activities are conducted to develop more complex control systems such as fuzzy, neural network, genetic algorithm, sliding mode, etc, the traditional control scheme of PID controller is still very much in use [9]. This is due to the simple and robust characteristics of the controller. It can work very well when it is operated under linear and steady state conditions. However, it cannot work well on a very complex condition and if the plant has a very non-linear properties [10]. Based on a survey which was conducted on over eleven thousand controllers used in the processing (food, oil and gas), chemicals, pulp and paper industry, 97% of those used PID controller [11]. This survey was conducted by Desborough et al. (2000) and was funded by Honeywell. Despite the fact that a wide range of control system architectures have been created, PID controller remains the first choice for a new control system developed by practitioners. This is because the reliability of a PID controller has been proven and it is easy to understand [12].

B. The System Block Diagram

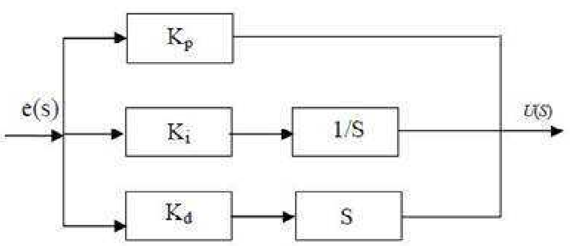

Figure 1. PID controller architecture [4]

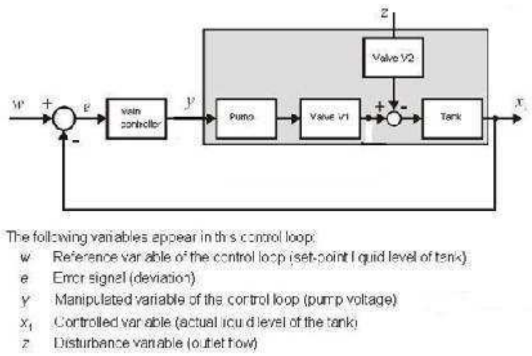

Figure 2. Block diagram

Figure 2 shows the block diagram that represents the system. Variable w is reference variable, also called the set point, which is the desired level inside the tank. Variable e is the error signal, which is the difference between set point and actual liquid level (in the tank). Variable y is the manipulated variable, which is the voltage value of the pump. Voltage pump is also called the actuator/driver response. Variable x_1 is the controlled variable, which is actual liquid level. Variable z is the disturbance variable, which is the flow of liquid out of the tank.

C. The Process System Schematic

The steady state level of the liquid inside the tank is kept constant by the flow of inputs and outputs that can change (usually the output flowing through the outlet valve is kept constant). Figure 3 illustrates the system schematic that is typically found in process engineering.

The system schematic comprises the following components:

1. The liquid tank T with the input is located at the upper left and the output is at the bottom of the tank.
2. Level sensor (LE 101) is used to measure the level of liquid inside the tank.
3. Inlet valve V1 (UV 102) is used to regulate the flow into the tank.
4. Outlet valve V2 (UV 103) is used to control the liquid discharge out of the tank.
5. Pump P (EU 104) is used to pump liquid into the tank from the reservoir.
6. Flow-rate sensor (FR 105) is used to measure the liquid flow rate that goes into the tank.

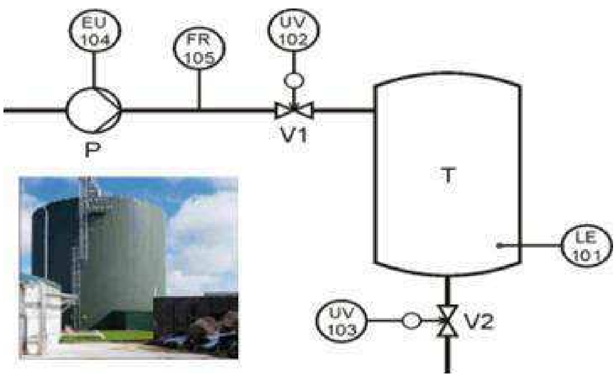

Figure 3. Typical illustration of the process system schematic

(a) (b)

Figure 4. (a). Liquid tank module; (b). UniTrain module

In this system, reference variable or set point is the desired liquid level in the tank. The volume of water flowing out of the tank can be controlled by adjusting the valves V2 and it can be considered as the system disturbance variable. The pump voltage functions as manipulated variable.

D. *UniTrain*

UniTrain is an integrated multimedia learning system which is very easy to move for the needs of teaching and training in electrical engineering field [13]. Two modules are required in these experiments. The first module is the liquid tank module which is equipped with a pressure sensor and pump (see Figure 4a). The other is the UniTrain module which acts as a bridge between the computer and the liquid tank module (see Figure 4b). The setting for PID parameters is done by using a card inserted into the UniTrain module while the set point is determined by the computer.

III. Method

Before the research is started, there are several things that need to be prepared:
1. A set of computer.
2. Two sets of software, UniTr@in Software Package and L@bsoft Control Technology Practical Introduction.
3. Liquid tank and UniTrain modules.
4. A digital multimeter.
5. A set of cable and one liter of distilled water.

A. *Software Installation*

The necessary software must be installed first. The tank is then filled with distilled water. The next step is to calibrate the level sensor.

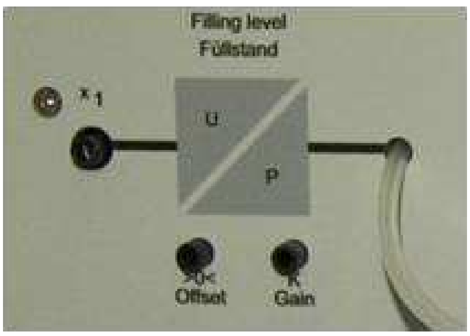

Figure 5. 'Offset' and 'Gain' potentiometers

B. *Sensor Calibration*

The sensor used to measure the water level is a pressure type sensor. When the water level increases, the pressure that the sensor detects is also getting higher. The increase of pressure is caused by the weight of liquid inside the tank. This pressure will be converted into voltage and the voltage value will be interpreted as the level of water inside the tank.

To get good results, firstly, the sensor needs to be calibrated. Sensor calibration can be done by two methods:

A.1 Manually calibrated (using a digital multimeter).

- Connect the liquid tank module to the power supply.
- Connect the positive cable of the multimeter to x_1 at the 'filling level' while the negative cable is connected to 0 V (ground).
- Discharge the tank by opening V2 valve to maximum, and then set the voltage to 0 V (see the voltage value on the multimeter) by using the 'Offset' potentiometer.
- Close the discharge valve V2 and open the inlet valve V1 to maximum. Fill the tank with water until it reach to the level of 100% (maximum tank height). Afterward, set the voltage reading on the multimeter to 10 V by using the 'Gain' potentiometer (see Figure 5).

A.2 UniTrain calibrated (using UniTrain and computer)

- Connect the liquid tank module to the power supply.
- Connect the tank and the UniTrain modules with cables as shown by Figure 6.
- Open voltmeter A from the L@bsoft, then set the voltmeter mode in AV and set the range by 20 V.
- Empty the tank by opening valve V2 to the maximum and set the voltage to 0 V (see the value in voltmeter A) via the 'Offset' potentiometer.
- Close the V2 valve and open inlet valve V1 to maximum.
- Open DC source from L@bsoft, then set the range by 10 V and set the output voltage (pump voltage) to 5 V. The pump will start and fill the tank with water until it peaks at the level of 100%. Next, set the voltage to 10 V (see voltmeter A) via the 'Gain' potentiometer.

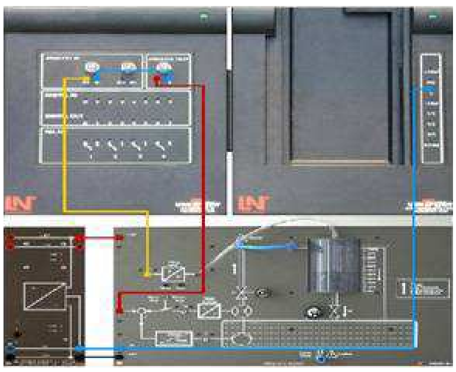

Figure 6. The wiring for sensor calibration

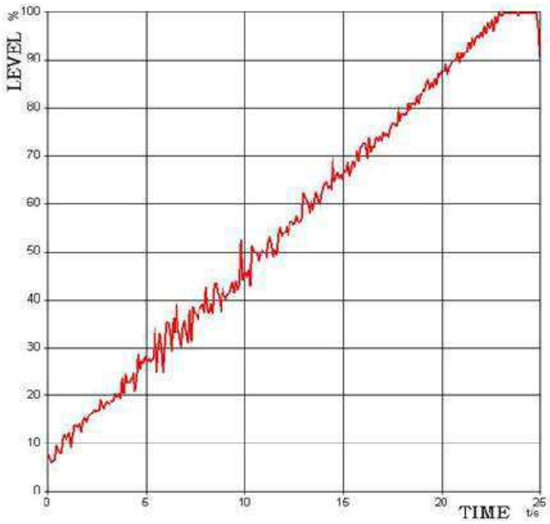

Figure 7. A well-calibrated sensor's response

C. *Sensor's Response*

After the sensor is calibrated, its response can be obtained by performing the following steps:

- Close outlet valve V2 and open inlet valve V1 to maximum.
- Open 'Step Response Plotter' from L@bsoft and set the configuration as shown in Table 1.

If the sensor is well-calibrated, then the response will make a linear line as demonstrated by Figure 7.

Table 1. The configuration for sensor's response

Scaling of axes				
X-axis	Min.: 0	Max.: 25	Division: 5	Marking: 1
Y-axis	Min: 0	Max.: 100	Division: 10	Marking: 1
Settings for inputs				
Channel A	Meas, range 10 V	Coupling: DC	Range: 100	Offset: 0
Channel B	Meas, range 10 V	Coupling: DC	Range: 100	Offset: 0
Setting for options				
Step change from		0 to 100%		
Delay time / ms:		0		
Number of measurements:		300		

IV. Results and Discussion

A. *PID Controller*

In these experiments, a card name 'PID Controller Card' is needed. The experiments can be generally divided into four categories.

A.1 P Controller

To do the P controller experiment, the following steps are required:

- Insert the 'PID Controller Card' into the UniTrain module and connect the circuit as shown in Figure 8.
- Empty the tank by opening V2 valve to maximum, then open V1 valve also to maximum and set the flow-rate switch to 'open loop' position in order to disable the automatic flow-rate control.
- Open 'Step Response Plotter' and set the configuration as shown in Table 2.
- Turn the P (K_P) controller switches on, then turns off the I (T_N) and D (T_V) controllers switch.
- Set the desired K_P value (the values are set as the following, $K_P = 1$, $K_P = 5$, and $K_P = 50$). The response can be seen in appendix 1, Figure A, B and C.

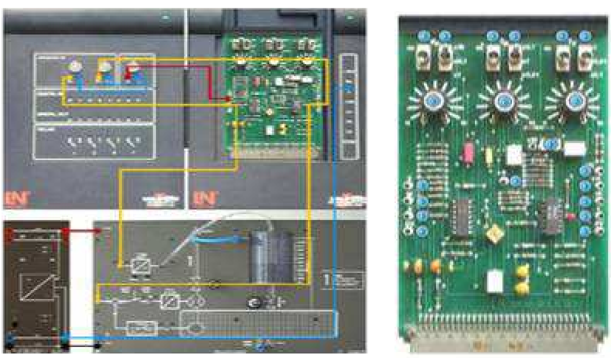
Figure 8. The wiring for PID experiment and the card

A.2 I Controller

To do the I controller experiment, the following steps are required:

- Perform steps a to c as demonstrated by part A.1 (P controller).
- Turn the I (T_N) controller switches on, and then turns off the P (K_P) and D (T_V) controllers switch.
- Set the desired T_N value (the values are set as the following, $T_N = 0.05$, $T_N = 0.5$, and $T_N = 5$). The response can be seen in Appendix 1, Figure D, E and F.

A.3 D Controller

Table 2. The configuration for PID controller experiments

Scaling of axes				
X-axis	Minimum: 0	Maximum: 120	Division: 5	Marking: 1
Y-axis	Minimum: 0	Maximum: 100	Division: 10	Marking: 1
Settings for inputs				
Channel A	Meas, range 10 V	Coupling: DC	Range: 100	Offset: 0
Channel B	Meas, range 10 V	Coupling: DC	Range: 100	Offset: 0
Setting for options				
Step change from		0 to 60%		
Delay time / ms:		0		
Number of measurements:		300		

The use of only derivative gain in a controller is not possible, because a stand-alone derivative produces 100% steady state error [14]. Thus the voltage pump output/ actuator response is nearly zero. The pump voltage needs to be strengthened by using proportional gain. K_P value will be made constant and T_V will be varied to observe the effect of derivative gain. The system responses will be compared to the P controller with the same K_P value. To do the experiment, the following steps are needed:

a. Perform steps a to c as demonstrated by part A.1 (P controller).
b. Turn the I (T_N) controller switches off, and then turns on the P (K_P) and D (T_V) controllers switch.
c. Set the desired K_P and T_V values. The values for K_P and T_N are varied as the following, (T_N = 0.05, T_N = 0.5, and T_N = 5). The response can be seen in appendix 1, Figure G, H and I.

A.4 PI Controller

To do the PI controller experiment, the following steps are required:

a. Perform steps a to c as demonstrated by part A.1 (P controller).
b. Turn the D (T_V) controller switches off, and then turns on the P (K_P) and I (T_N) controllers switch.
c. Set the desired K_P and T_N values. The values are set as the following, K_P = 0.5 and T_N = 2, K_P = 0.5 and T_N = 0.2, K_P = 5 and T_N = 0.2. The response can be seen in appendix 1, Figure J, K and L.

B. Discussion

Each element of the PID controller has unique effects on the system. The proportional gain (K_P) has the effect to reduce the rise time (rise time), and it also reduces steady-state error though it never completely eliminates the steady-state error. The integral gain (K_I) has the effect to eliminate the steady-state error completely, but it delays the response and increases the overshoot. Derivative gain (K_D) has the effect to increase the stability of the system by shifting closed-loop pole to the left-hand side of the s-plane. It also reduces the overshoot, but it does not have any effect on steady-state error. Several effects of P, I, and D parameters have been summarised in Table 3.

B.1 P Controller

The results from section A.1 (P controller) demonstrate the characteristics of proportional gain. Steady-state error is defined as the difference between input and output of the system in the limit as time goes to infinity [15]. Steady-state error can be calculated as follow:

$$e_{ss} = \lim_{t \to \infty} (w - x_1(t)) \quad (1)$$

where w is a constant reference or set point and x_1 is the actual height of liquid inside the tank. The steady-state error for a step response is also often reported as percentage, similar to the overshoot (see equation 2).

Table 3. PID parameters characteristics

Closed-Loop Response	Rise Time (Waktu Naik)	Overshoot	Settling Time	Steady-State Error (Kesalahan Tunak)
K_P	Decrease	Increase	Small Change	Decrease
K_I	Decrease	Increase	Increase	Eliminate
K_D	Small Change	Decrease	Decrease	No Change

$$e_{ss} = \frac{reference - final\ value}{reference} \times 100\% \quad (2)$$

The ‘final value’ is the real/exact liquid height inside the tank when the system has reached the steady-state conditions. The range for K_P is 0-100 (the range limit is set by the PID controller card). For K_P = 1, the steady-state error obtained is very large at around 93.33%. For K_P = 5, the steady-state error obtained is reduced about 26.66%. For K_P = 50, the steady-state error obtained is even less, at around 5%, compared to the other K_P values. The increase of K_P reduces the system steady-state error. However, the steady-state error cannot be entirely eliminated, even though the proportional gain has been raised to available maximum value (K_P = 100). This is consistent with the characteristics of proportional element (see Table 3).

The range for voltage pump is between 0 V to 10 V. For K_P = 1, the voltage pump reaches the maximum value of about 6.6 V in a very short time (less than 1 second), then it slowly drops and stabilises at about 6.4 V. For K_P = 5 and K_P = 50, the maximum value of voltage rises to the highest range (10 V) very fast. At K_P = 5, the actuator response/pump voltage began to drop approximately after 18 seconds and when the system reaches it steady-state the response varies within the limits of about 6.7-7.8 V. At K_P = 50, the response voltage begins to drop after 32 seconds and when the system stability is reached, the voltage varies between maximum and minimum range. This is due to the characteristic of the proportional gain which amplifies the noise within the system. As K_P increases, the noise also multiplies proportional to the value of K_P. Systems that have noises are not recommended to have a very large K_P.

The response for the actuator and liquid level for K_P = 1, K_P = 5, and K_P = 50 are shown in Appendix 1, Figure A, B, and C.

B.2 I Controller

The results from section A.2 (I controller) demonstrate the characteristics of integral gain. The value of T_N = KI and range for T_N is between 0.01-100 (the range is determined by the PID controller card). Appendix 1, figure D, E, and F show that apparently the responses do not have steady-state error. Furthermore, the increase of T_N

raises the system's overshoot, thus system response will be oscillating. Overshoot is often presented as percentage and the calculation can be seen in Equation 3, where final value is equal to set point, because the steady-state error is zero.

$$\%OS = \frac{\text{maximum level-final value}}{\text{final value}} \times 100\% \quad (3)$$

For $T_N = 0.05$, the overshoot is more or less 3.33%. For $T_N = 0.5$, approximately 8.33% overshoot is obtained and also a delay for about 2 seconds appears in the system's response. For $T_N = 5$, the overshoot is increased around 11.67% and the delay also escalates to 12-13 seconds. This is consistent with the characteristics of integral element.

For $T_N = 0.05$, the voltage pump reaches to about 9.9 V in roughly 1 second, then the voltage decreases sharply after about 37 seconds and oscillates between 6.1- 9.3 V. For $T_N = 0.5$, the actuator response shows a delay for 2 seconds before the voltage pump increases to approximately 9.8 V. After that, the voltage begins to drop and oscillates. The oscillation that occurs is damped gradually towards a certain voltage value. For $T_N = 5$, the delay increases to 10 seconds and the time required for the voltage pump to reach maximum value of 9.7 V is about 10 seconds. After that, the voltage decreases gradually and the oscillation that occurs reduces to a certain voltage value. The actuator responses are quite smooth. It means that the integral gain can handle the system's noise sufficiently.

The response for the actuator and liquid level for $T_N = 0.05$, $T_N = 0.5$, and $T_N = 5$ are shown in appendix 1, Figure D, E, and F.

B.3 D Controller

The results from section A.3 (D controller) demonstrate the characteristics of derivative gain. Derivative controller can never be used alone, because the derivative gain differentiates the error signal to zero. Therefore, a pure derivative controller produces steady-state error of 100%. To avoid this, the derivative element is always paired up with other element(s) in the form of PD or PID controller. In section A.3, PD controller is used in order to see the characteristics of derivative gain.

The value of $K_D = T_V$ and has a range from 0-10 (the range is set by the PID controller card). It can be seen from the response in appendix 1, Figure G ($K_P = 50$), K ($K_P = 50$, $T_V = 0.05$), L ($K_P = 50$, $T_V = 0.5$), and M ($K_P = 50$, $T_V = 5$), that the changes in T_V do not have any effect on the system steady-state error. It can also be seen from the response, that there is a slight change in the rise time between the system with only proportional element and the system with derivative plus proportional elements. This is consistent with the characteristics of the derivative element.

Derivative gain is rarely used in systems with PID controllers, especially for system with noise like the miniature tank in this research, because the derivative element amplifies the noise within it. This can be seen from the actuator response shown in appendix 1 (Figure K, L and M). When the system enters the steady-state condition, the voltage pump starts to vary in a very large range (0-10 V). Of course this behaviour needs to be avoided because if the pump has a very high frequency of 'on and off' condition, it will reduce the life expectancy of the pump (the pump will be broken sooner than it normally does).

The response for the actuator and liquid level for $T_V = 0.05$, $T_V = 0.5$, and $T_V = 5$ are shown in appendix 1, figure K, L, and M. The proportional gain for all T_V is set constant at $K_P = 50$.

B.4 PI Controller

For plant such as liquid tanks, the most important characteristics are the level precision of liquid and faster filling time; thus the set point can be reached quickly and accurately. In other words, the system needs a fast rise time, a small overshoot, and no steady-state error. Therefore, with these characteristics, the most appropriate PID controller is a PI controller.

In this type of system, the addition of derivative element is unnecessary because it does not give a significant impact on the desired system characteristics. On the contrary, it makes the controller architecture more complex. Another reason why the derivative gain is not used is because it is not suitable for a system with noise to have a derivative element. It amplifies the noise and shortens the pump's usage time as discussed in section B.3.

Based on proportional and integral gain characteristics, which have been discussed in section B.1 and B.2, the value for K_P and T_N that able to meet the desired system characteristics is a medium (not too small or not too large) K_P and a small T_N. Medium K_P value will increase the rise time and reduce the steady-state error, while a small T_N value will eliminate steady-state error, reduce the overshoot and minimise the delay time. A large K_P is not particularly appropriate for this system because the noise is multiplied by the proportional gain. This leads to the fluctuation of the pump voltage between maximum and minimum range. A large T_V is also not appropriate because it makes the system have large delay and large overshoot; both are undesired traits for the system.

Appendix 1, Figure N, O, and P show some combination of K_P and T_N values. The method used to find the combination is 'trial and error' method. From these responses, a good combination is $K_P = 5$ and $T_N = 0.2$.

V. Conclusion

Increasing proportional element can reduce the steady-state error. However, it cannot eliminate the error entirely. Proportional element also amplifies the noise within the system. Therefore, system with noise is not recommended to have a very large K_P. Integral element can handle noise well. It can also eliminate steady-state error completely.

However, the increase of integral element can raise overshoot and delay time. Pure derivative gain cannot be used alone in a controller, because it differentiates the error signal and the result is zero. This means that the controller generates 100% steady-state error, thus derivative gain is always combined with other elements in the form of PD or PID controller.

Derivative control is unnecessary for controlling the liquid tank system because it does not give a substantial outcome in overall system. Furthermore, a system with noise such as this, the addition of derivative gain will just create a bad result. PI controller is the most apposite controller to control the tank liquid level automatically. By using proportional and integral elements, the set point can be reached quickly with zero steady-state error. K_P and T_N values need to be carefully set in order to minimise the overshoot and delay time. A good combination is $K_P = 5$ and $T_N = 0.2$.

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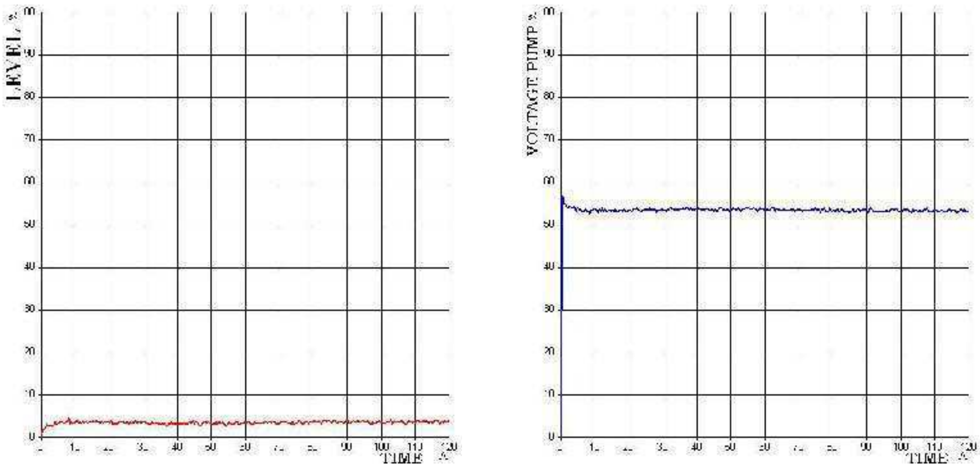
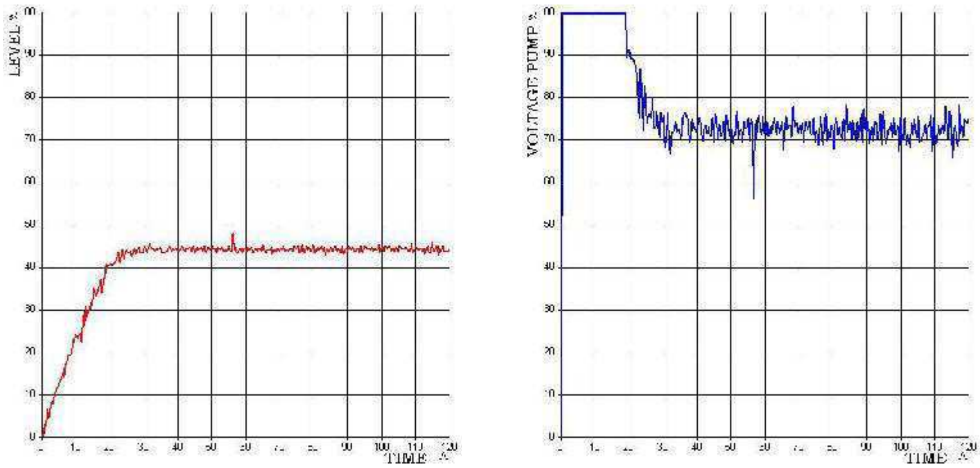
APPENDIX 1



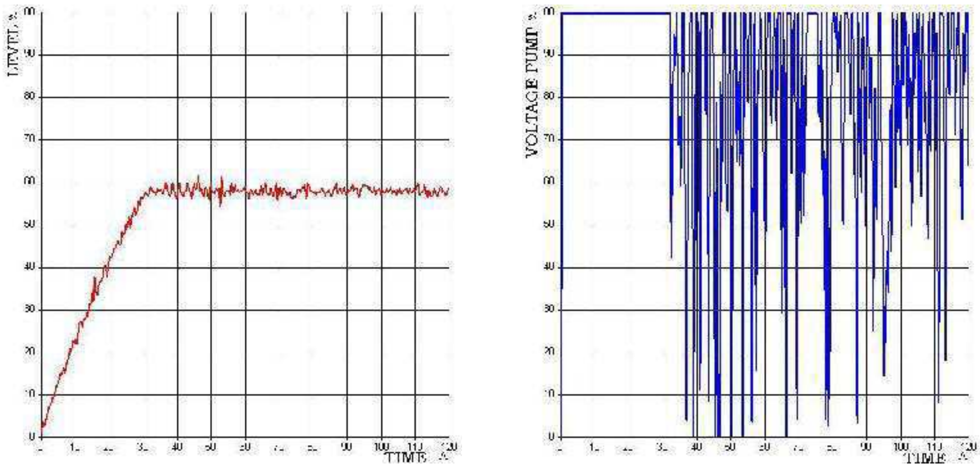
(a) (b)

Figure A. The system step response (a) and the actuator response (b) for K_P =1



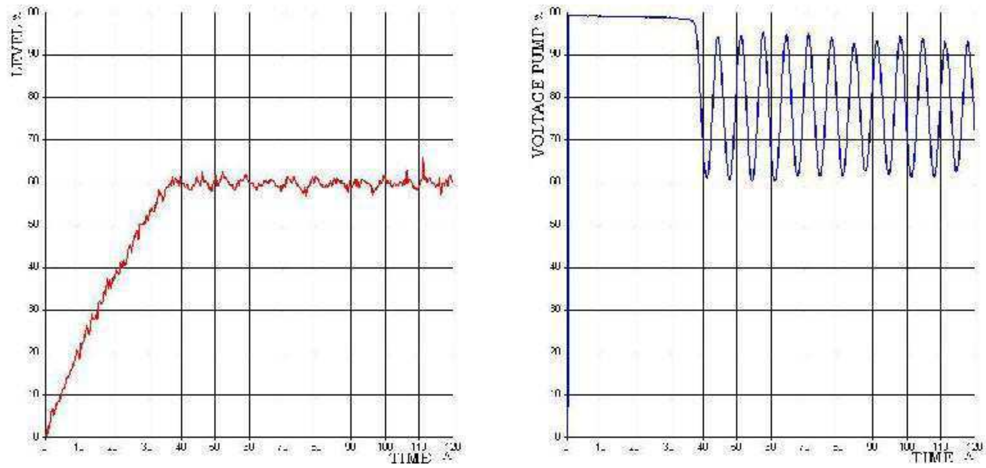
(a) (b)

Figure B. The system step response (a) and the actuator response (b) for K_P =5



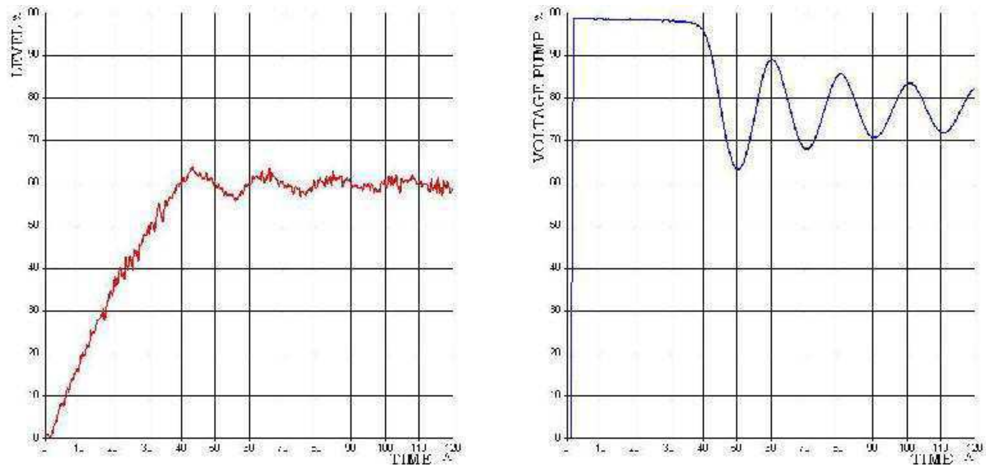
(a) (b)

Figure C. The system step response (a) and the actuator response (b) for K_P =50



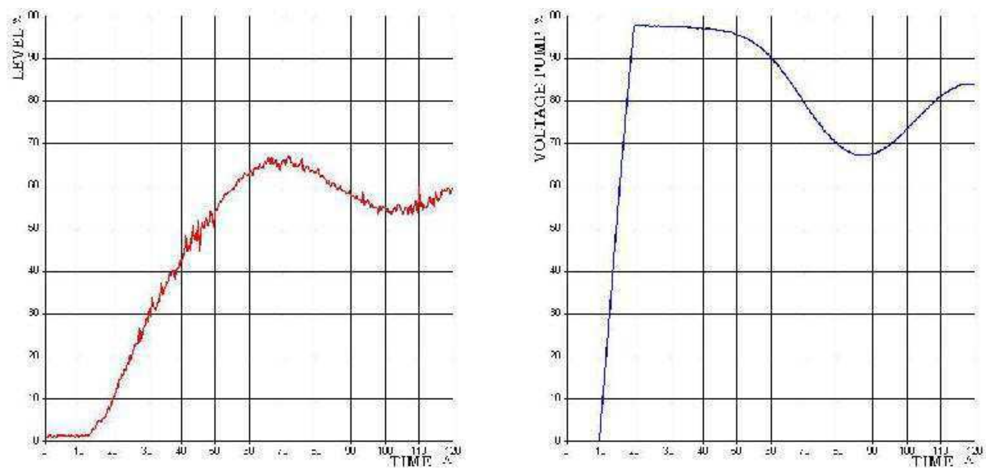
(a) (b)

Figure D. The system step response (a) and the actuator response (b) for T_N =0.05



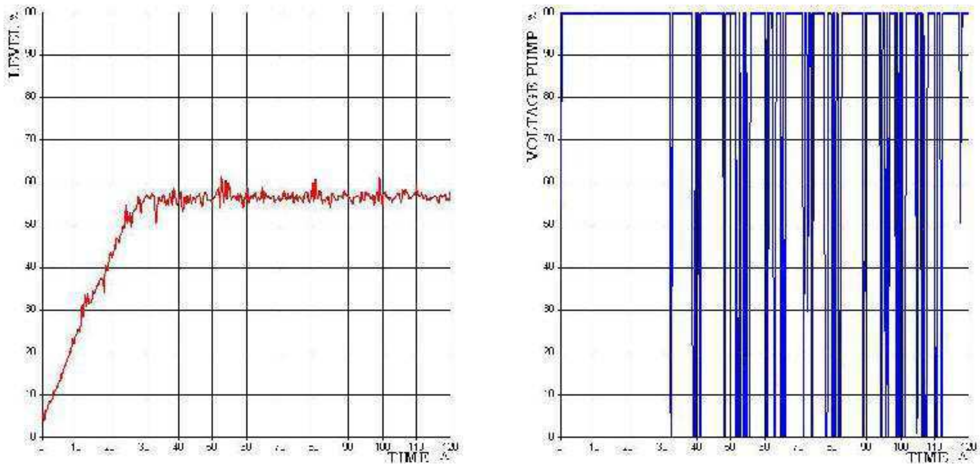
(a) (b)

Figure E. The system step response (a) and the actuator response (b) for T_N =0.5



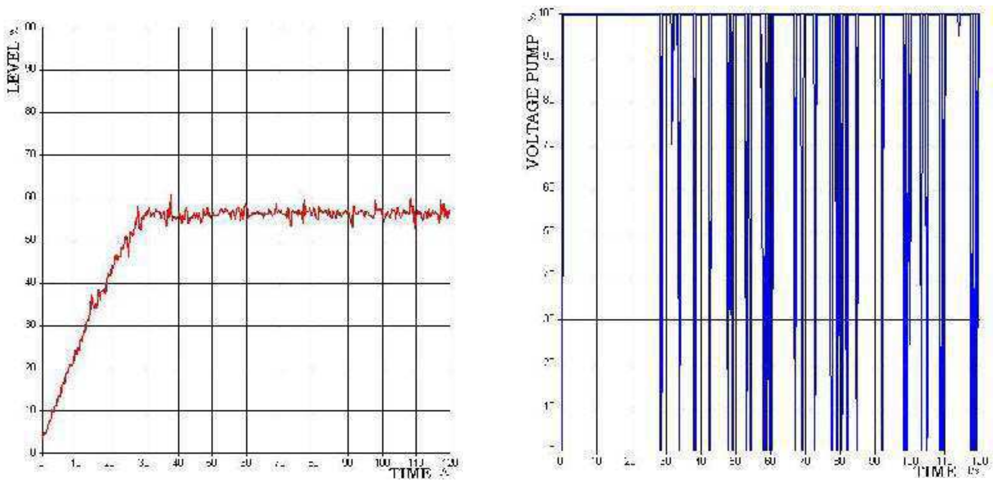
(a) (b)

Figure F. The system step response (a) and the actuator response (b) for T_N =5



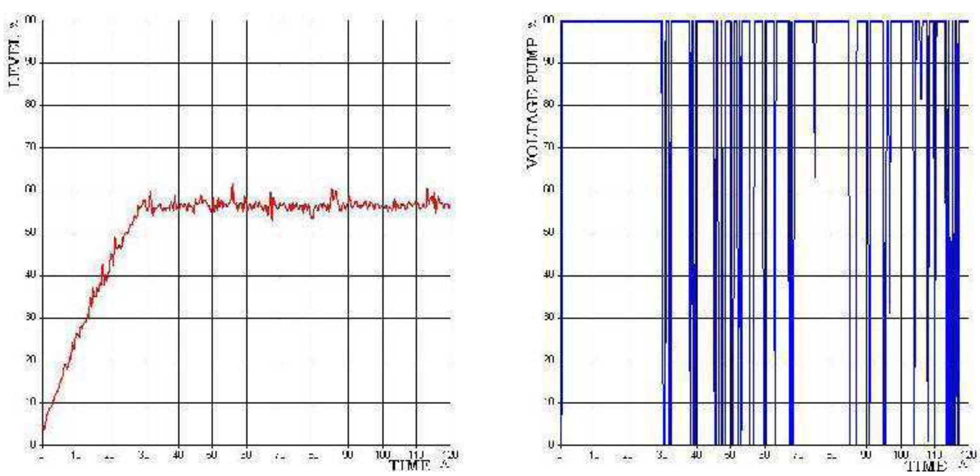
(a) (b)

Figure G. The system step response (a) and the actuator response (b) for $K_P = 50$, $T_V = 0.05$



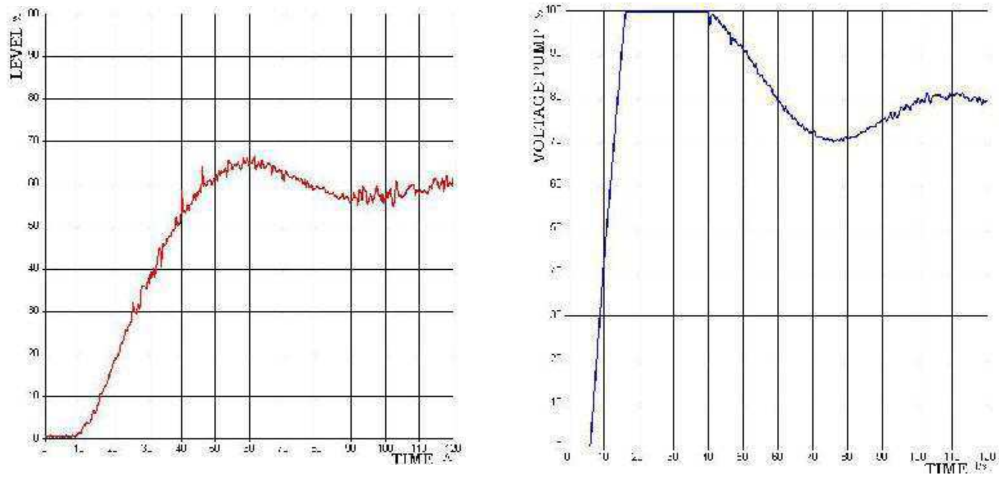
(a) (b)

Figure H. The system step response (a) and the actuator response (b) for $K_P = 50$, $T_V = 0.5$



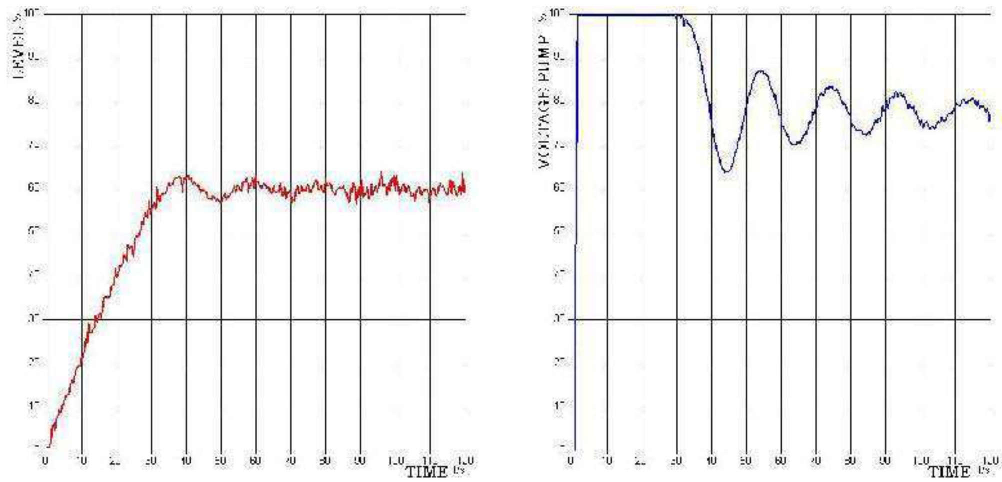
(a) (b)

Figure I. The system step response (a) and the actuator response (b) for $K_P = 50$, $T_V = 5$



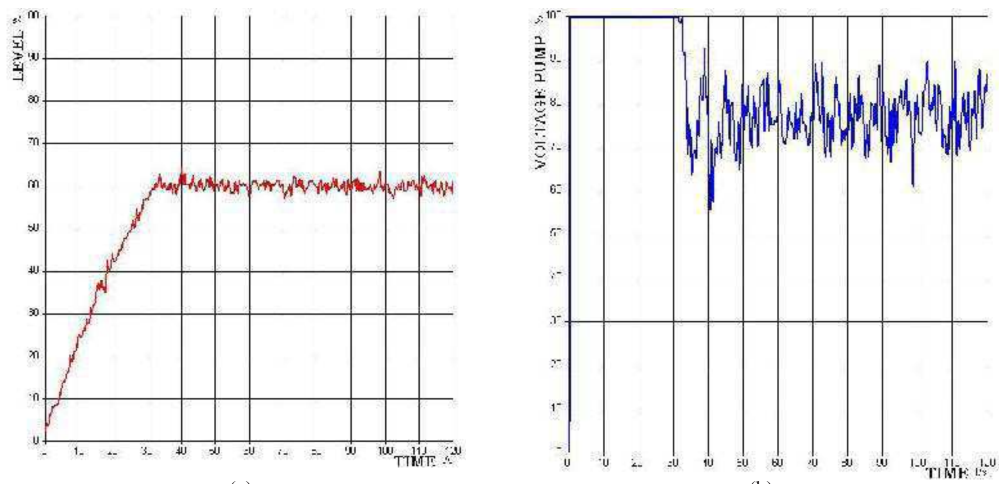
(a) (b)

Figure J. The system step response (a) and the actuator response (b) for $K_P = 0.5$, $T_N = 2$



(a) (b)

Figure K. The system step response (a) and the actuator response (b) for $K_P = 0.5$, $T_N = 0.2$



(a) (b)

Figure L. The system step response (a) and the actuator response (b) for $K_P = 5$, $T_N = 0.2$

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