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UNDERWATER VEHICLE BUOYANCY CONTROL (SURFACE)

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Bachelor of Electrical Engineering
(Control, Instrumentation and Automation)

Jun 2014

“I hereby declare that I have read through this report entitle “Underwater Vehicle Buoyancy Control (Surface)” and found that it has comply the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering (Control, Instrumentation and Automation)”.

Signature : ....

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Date : ....

UNDERWATER VEHICLE BUOYANCY CONTROL (SURFACE)

KHAIRUL HAFIZ BIN SHAFAD

A report submitted in partial fulfillment of the requirements for the degree of Bachelor of Electrical Engineering (Control, Instrumentation and Automation)

Faculty of Electrical Engineering

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2014

"I hereby declare that this report entitle "Underwater Vehicle Buoyancy Control (Surface)" is the result of my own research except as cited in the references. This report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree

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Name : ....

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Specially dedicated to my family, lecturers and friends.

Thanks for all the encouragement and support

.

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ABSTRACT

In general the Remotely Operated Vehicle (ROV) consists of two methods which are using thruster and buoyancy control. Since the thruster required high power demand, so this project will used ballast tank as buoyancy control based on the Archimedes principle. This project consists of three objectives which are to design a ballast tank, to design PID controller in order to improve the performance of the ballast tank, and to compare the algorithm system of the ballast tank between the system control level from surface and the system control level from bottom. Pressure sensor from model MPX4250GP is used in this project as control feedback system. Besides, pressure sensor also converts analog input to voltage (v) in order to compare with desired input set. In this project, mechanical design will focus on the construction of the ballast tank that can move the piston to pump water in and pump water out effectively. Next, PID controller will be implemented in the real hardware in order to improve the performance of the ballast tank. This PID controller will be design by using PID tuning method in the Matlab. Experiment results shown that the system with PID controller is able to perform better performance in term of rise time and settling time, and able to maintain disturbance up to 120g for 300rpm and 80g for 200rpm. At the end of this project, the algorithm system of the ballast tank have been compared between the system control level from surface and the system control level from bottom. It is found that future ballast tank can use both algorithms system (by switching) to control depth level based on suitable depth error.

ABSTRAK

Secara umum, “Remotely Operated Vehicles” (ROV) terdiri daripada dua kaedah iaitu dengan menggunakan pendorong dan kawalan keapungan. Oleh sebab, pendorong memerlukan kuasa yang tinggi, maka projek ini akan mengunakan tangki sebagai kawalan keapungan berdasarkan prinsip Archimedes. Projek ini terdiri daripada tiga objektif, iaitu untuk mereka bentuk tangki, untuk mereka bentuk pengawal PID untuk meningkatkan prestasi tangki, dan untuk membandingkan sistem algoritma tangki antara kawalan sistem dari permukaan dan kawalan sistem dari bawah. Sensor tekanan daripada model MPX4250GP digunakan dalam projek ini sebagai sistem kawalan maklum balas. Selain itu, sensor tekanan juga menukarkan masukan analog kepada voltan (v) untuk membandingkan dengan set masukan yang dikehendaki. Dalam projek ini, reka bentuk mekanikal akan di tumpukan kepada pembinaan tangki yang boleh menggerakkan omboh untuk mengepam air ke dalam dan mengepam air keluar dengan berkesan. Seterusnya, kawalan PID akan dilaksanakan dalam perkakasan sebenar untuk meningkatkan prestasi tangki. Kawalan PID ini akan di reka dengan menggunakan kaedah “PID tuning method” di dalam Matlab. Hasil ujikaji menunjukkan bahawa sistem dengan pengawal PID mampu melakukan pr estasi yang lebih baik dari segi masa naik dan masa penetapan, dan mampu mengekalkan gangguan sehingga 120g untuk 300rpm dan 80g untuk 200rpm. Pada akhir projek ini, algoritma sistem tangki telah dibandingkan antara tahap kawalan sistem dari permukaan dan peringkat kawalan sistem dari bawah. Ia didapati bahawa tangki masa depan boleh mengunakan kedua-dua sistem algoritma (dengan beralih) untuk mengawal tahap kedalaman yang berdasarkan kesilapan kedalaman yang sesuai.

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CHAPTER 1

INTRODUCTION

1.0 Introduction

The aim of this chapter is to describe in general about underwater vehicles. The problem statement is identified based on regarding problem and the objectives are created in order to solve this problem statement. Then, the project scope will be mentioned the limitation of this project.

1.1 Project Background

Remotely Operated Vehicles (ROV) is essentially an underwater robot that is widely used in lot of underwater exploration such as industrial, marine study or work [1]. The ROV is used for operation either in hazardous environment or at high depths pressurized where human cannot withstand. The applications of the ROV can be seen in exploring hydrothermal vents, surveying archaeological sites, and fixing underwater infrastructure such as cabling and piping, mostly construction of oil facilities and offshore gas [1]. There are two mains part in the ROV which are mechanical part and controlling part that used to protect the electronic component. Figure 1.1 shows example of ROV prototype model. A ROV differs from autonomous underwater vehicle (AUV) in a way that ROV always take command from its operator and takes no action autonomously [2].

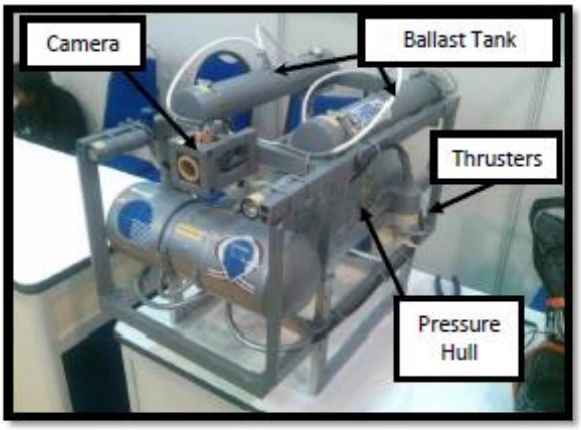


Figure 1.1 : Prototype of UTeRG ROV [3]

The main drawback in current underwater tasks performance is that, the components used such as thruster, lamp and camera consumed high power usage. Therefore, in order to solve high power consumption problems, one of the best ways is performing ROV operation without thruster [4]. Drawback of thruster also had proved by the research conducted by National Oceanic and Atmospheric Administration (NOAA) discover that the performance of the thruster become worst when reaching the saturated point at depth pressure is high[3]. Then, the ROV will no longer can be move downward at this saturated point. Since the thruster will not give good performance in underwater tasks, another alternative method to replace thruster is ballast tank. Ballast tank use the concept of the buoyancy force corresponds to displacement of water. When the ballast tank is filled with water, the ROV will add its weight, so the ROV will move downward. Other than that, by using ballast tank also can make the ROV travel deeper in the underwater application. Figure 1.2 shows the comparison of the performance.

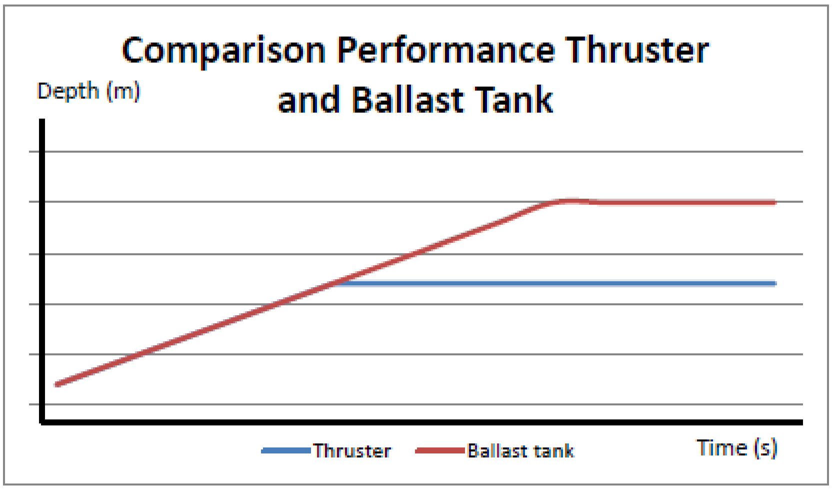


Figure 1.2 Comparison of thruster and ballast tank performance against depth[3]

Pressure sensor from model MPX4250GP is used in this project to detect the water level pressure and also used as feedback system in order to control the piston movement. Therefore, this pressure sensor can help the ballast tank to estimate and maintain at certain depth from the water surface.

1.2 Project Motivation

There a certain limitation when dealing with the underwater exploration such as risk of harsh environment and variety of problems. Figure 1.3 shows the relationship of temperature, salinity, and pressure when the depth is more increase.

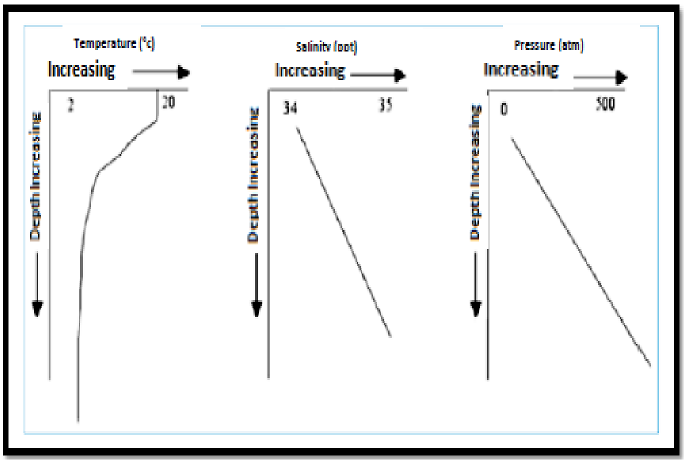


Figure 1.3: Variation of depth against temperature, salinity, and pressure [3]

Based on Figure 1.3 shows that temperature is decreasing when the depth increase. However, the salinity and pressure is increased linearly with depth increase. Human need to carry oxygen tank and suitable clothes in order to protect their body. This might possible to be not function and will cause risk to human. Hence, it is not suitable for a human to do an exploration under depth water level. Then, ROV will be used to replace the human in performing a high risk during underwater. Therefore, the main motivation of this project is to control the buoyancy of the ballast tank model.

1.3 Problem Statement

When performing underwater task, minimum power consumption is required to maintain at certain depth. There are two types of buoyancy control which is either using thruster or ballast tank. However, thruster required high power consumption to control buoyancy compared to ballast tank. Therefore, the ballast tank is more suitable to be used in this project to control buoyancy.

Based on the previous underwater vehicle final year project was developed by last year UTeM student, it seems that the objective to buoyant the remotely operated vehicle (ROV) in the desired depth was not achieved because the limitation design of ballast tank. The ballast tank was too small and can pump in the water only for a small quantity. Thus, the vehicle cannot achieve to maintain 5m based on the objective set. Therefore, the main goal of this project is to design the ballast tank based on the objectives set.

1.4 Objective (s) of the Project

The objectives of this project are to:

1. To design a ballast tank.
2. To design proportional integral and derivatives (PID) controller in order to improve the performance of the ballast tank system.
3. To compare the algorithm system of the ballast tank between the systems control level from surface and the system control level from bottom.

1.5 Project Scope

The scopes of work for this project are:

1. Design a new ballast tank in order to overcome last year's problem.
2. Using proportional integral and derivatives (PID) control system in (MATLAB) and Arduino microcontroller to improve performance of ballast tank.
3. The ballast tank movements only focus in one degree of freedom (up and down).
4. The ballast tank is tested at laboratory pool which has maximum depth of 1.2m.
5. The ballast tank can maintain up to 30cm for open loop system, while at 50cm at close loop system.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter will describe general concepts about the underwater vehicles and the ROV. This literature review will explain the factor that affecting the buoyancy, type of sensor uses, types of ballast tank, stepper motor, and microcontroller. Besides that, this chapter also will review on other people research regarding to underwater vehicles using buoyancy concept. This chapter also will conclude the proposed design for this project after analyze all the facts, data, information, and study on previous research.

2.1 Underwater Vehicle Classification

There are two different categories to classify the underwater vehicles. These two categories are manned underwater vehicles (MUV) and unmanned underwater vehicles (UUV). The first category MUV is divided into sub-classes that are military submarine and non-military submarines. This submarine type allow human to descend into ocean to perform military task and gather information by observation [5]. Next, the second category UUV can be separate into two branches that are Autonomous Underwater Vehicles (AUV) and Remotely Operated Vehicles (ROV). AUV class is intelligence which allows it to perform task autonomously, while for ROV need remotely control by a human when performing some task. This project is in ROV class. Figure 2.1 shows the category of underwater vehicles.

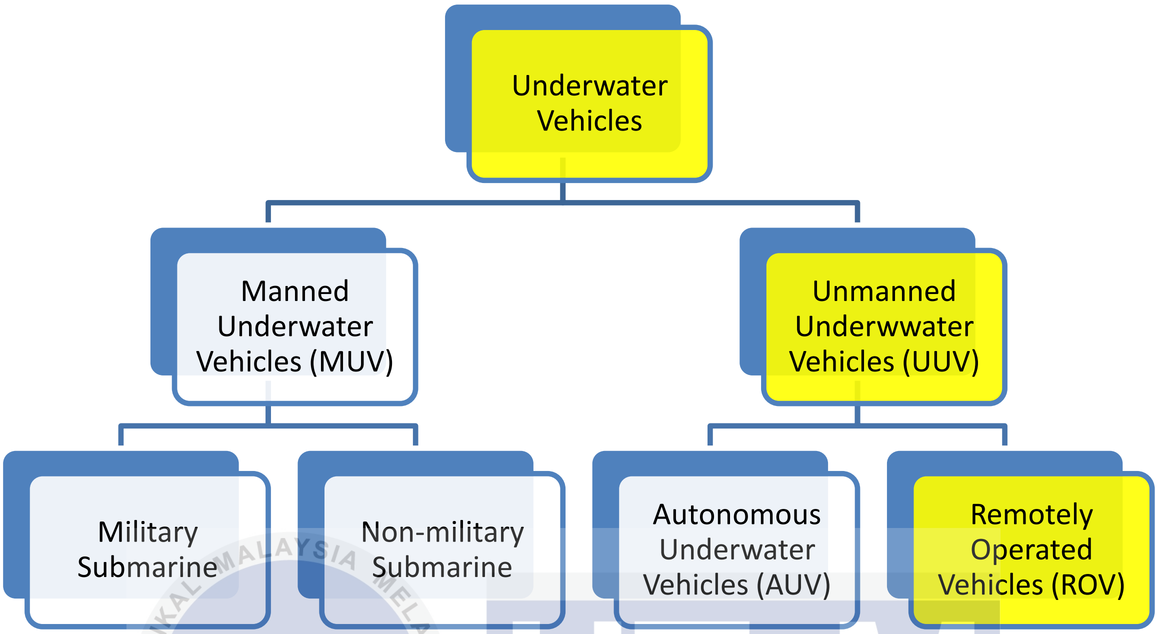


Figure 2.1: Underwater vehicles classification [5]

2.2 Factor affecting ROV Buoyancy Control

The factors such as buoyancy, stability, added mass, pressure and environmental force are needs to be considered when designing ballast tank. These factors will help to design a ballast tank that has a good performance and most important to meets requirement. Ballast tank is the practice adding, removing, or relocating weight of floatation on an underwater vehicle to correct its buoyancy and pitch and roll [6].

2.2.1 Buoyancy

Buoyancy is the upward force exerted by the fluid on a body that is immersed [6]. Buoyant force is the force different between large pressure pushing up under object and the small force pushing down over the object as shown in Figure 2.2.

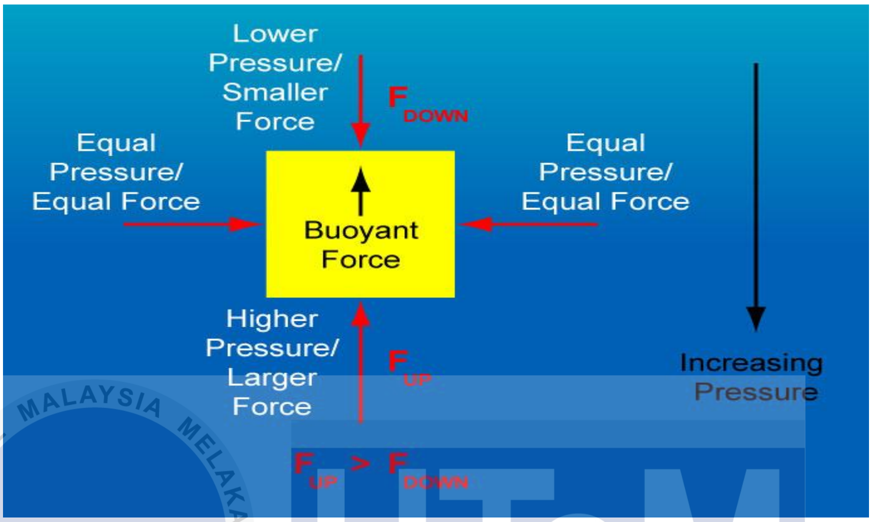


Figure 2.2: The net force of the fluid acting on an object is the buoyant force [6]

Based on the Archimedes Principle, magnitude of the upward force (buoyant force) of an object immersed in a fluid is equal to magnitude of weight of fluid displaced by object [6]. Figure 2.3 shows the weight of water displaced by the object.

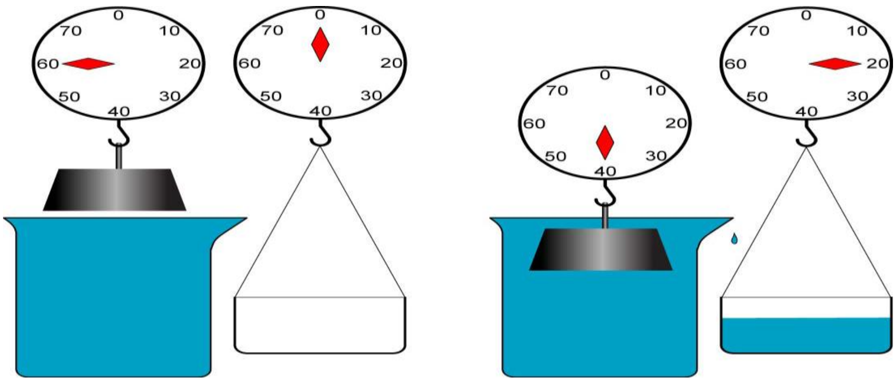


Figure 2.3: Archimedes principle [6]

Underwater vehicles will float or sink depended upon on the net effect of the weight of the object and the buoyant force generated by the object. There are three possible conditions for the object as shown in Figure 2.4 [6].

- Positive buoyancy: buoyant force > weight, the object floats
- Neutral buoyancy: buoyant force = weight, the object neither floats or sinks
- Negative buoyancy: buoyant force < weight, the object sinks

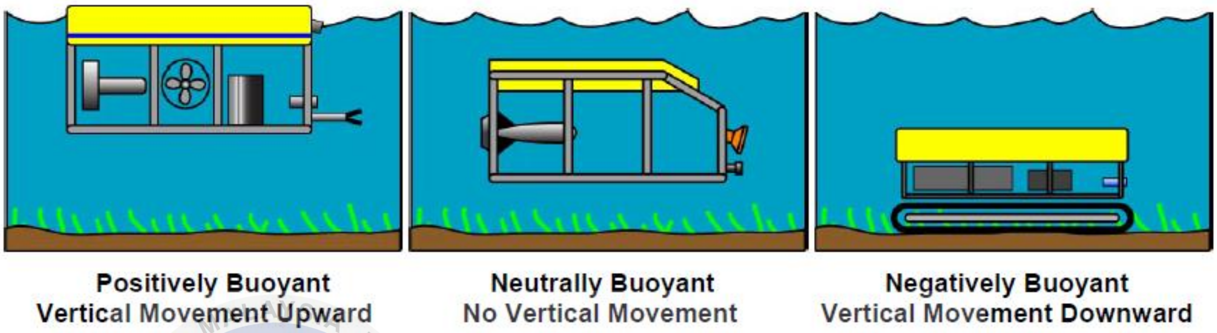


Figure 2.4 Positive, neutral, and negative buoyancy [6]

2.2.2 Added Mass

If the vehicle is too positively buoyant, the external mass can be added inside the pressure container. There is no displaced additional water (Archimedes Principle) occur and also no added buoyant force to the vehicle [6]. The best ways is by having a bolt for washer at each corner of the vehicle to make sure the vehicle is sits well in the water.

2.2.3 Pressure

Air and other gases easily compress when underwater compare to liquids and solids. Boyle's Law is used to predict result of introducing a change in volume and pressure only with the initial state of fixed quantity of gas [7]. Volume and pressure can be related to equation (2.1) below;

$$P_1V_1=P_2V_2 \quad (2.1)$$

Figure 2.5 shows the pressure is increased when depth goes deeper. Thus, this will affect the volume of gases and became smaller that previous volume. Therefore, this can be concluded that the pressure and the volume are inversely proportional.

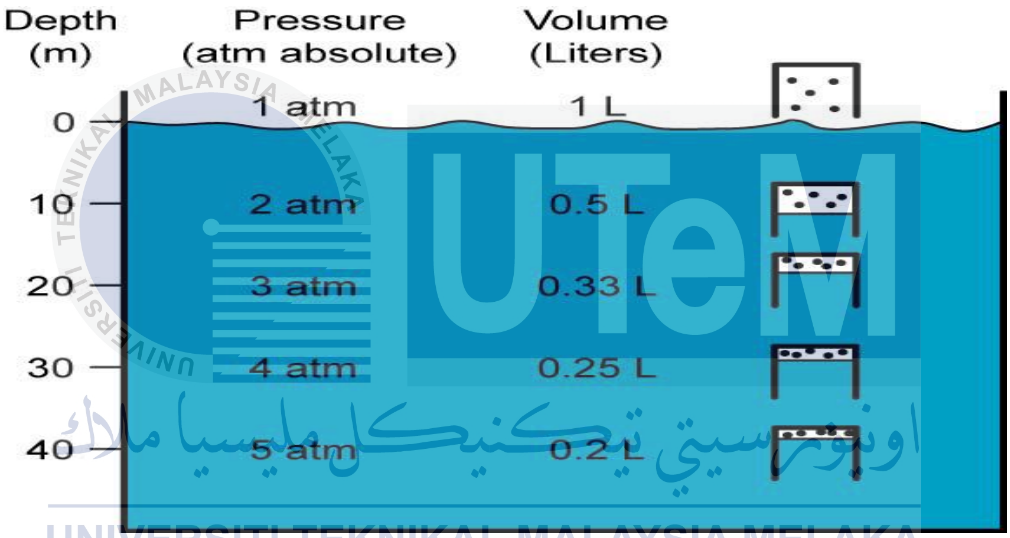


Figure 2.5: Liter beaker of air conforming to Boyle's Law under water [7]

2.2.4 Environmental Force

Environmental force such as wind and wave can cause ROV unstable. This environmental force can be ignored if ROV is fully submerged. However, currents still become prime disturbance for ROV. Environmental force also can be minimizing or eliminate if ROV is tested at the swimming pool or at the underwater lab pool.

2.3 Weight Estimation

ROV prototype can be predicted either float or submerge underwater based on the weight estimation calculation. The concept of Archimedes principle on buoyant force can be applied to this weight estimation calculation based on Archimedes principle as shown in equation (2.2) below [5];

$$F_b=\gamma_f V_d \tag{2.2}$$

Where:

F_b = Buoyant Forces

γ_f = Specific Weight of liquid

V_d=Displaced volume of the liquid

When object is floating [5]:-

$$F_b = W = \gamma_f V_d \tag{2.3}$$

If object has positive buoyant force, this object can be submerged by adding an external load. Refer to equation (2.4) below [5];

$$F_b = W + F_e = \gamma_f V_d \tag{2.4}$$

Figure 2.6 shows an example to calculate the force acting on the ROV prototype [5], while table 2.1 shows the acting force on the ROV.

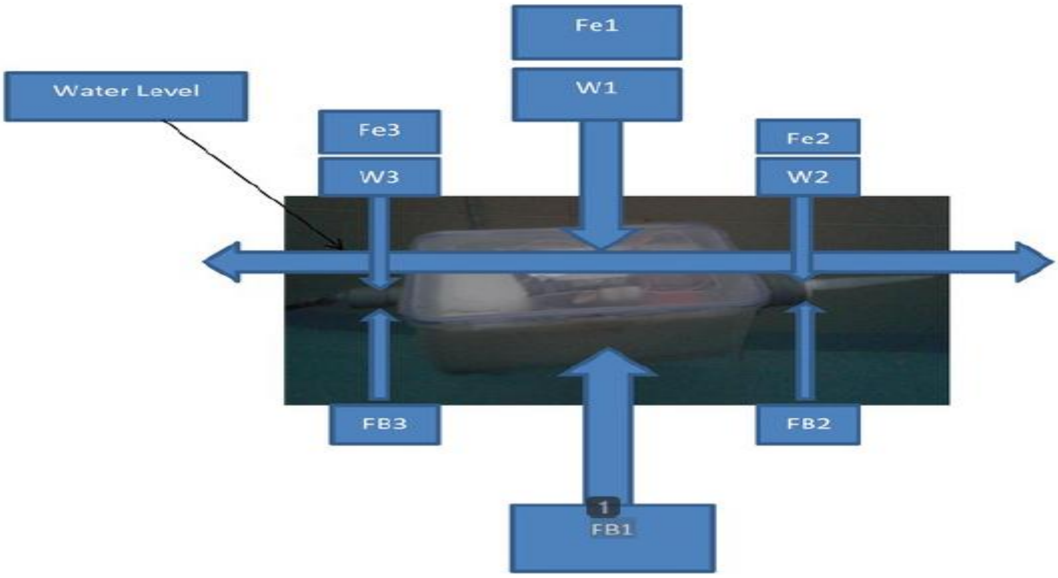


Figure 2.6: Force acting on the ROV prototype [5]

Table 2.1: Acting forces [5]

Part	Positive Forces	Negative Forces
Main Body	FB1	W1+Fe1
Ballast Tank	FB2	W2+Fe2
PVC	FB3	W3+Fe3

2.4 Types of Ballast Tank

Ballast tank can be used to control buoyancy and ballast tank also has ability to hold water without any leakage[8]. Ballast tank needs to be well-designed in order to make sure that it can protect the electronic component inside. There are many type of ballast tank that can be constructed. Basically, there are three types of ballast tank used for a small project and low cost [5]:

a) Mechanical attenuated system
   - i) Bellow ballast tank
   - ii) Piston ballast tank
   - iii) Membrane ballast tank

b) Pump system
   - i) Pressure tank
   - ii) Flexible tank

c) Gas operated
   - i) Liquid gas
   - ii) Pressurized air
   - iii) $C0_2$

Table 2.2 shows the comparison types of ballast tank based on buoyancy control and construction.

Table 2.2: Differences between types of ballast tank [5]

Types of ballast tank	**Mechanical attenuated system**	**Pump system**	**Gas operated system**
Buoyancy control	Accurate	Slightly accurate	Very accurate
Construction	Quite simple	Simple	Complex

Mechanical attenuated system has accurate buoyancy control compare to pump system. Even tough, gas operated system has very accurate compared to others, but construction is complex. Besides, construction for mechanical attenuated is quite simple, thus can reduce space and safe cost. In this project, piston ballast tank is selected because easy to construct compared to bellow ballast tank and membrane ballast tank.

2.5 Pressure Sensor

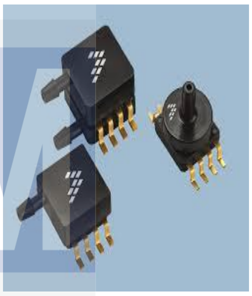
Pressure sensor can be used to measure liquids or gases. Variable such as water level, gas or fluid flow, and altitude can be measured by using pressure sensor. Basically, pressure sensor will act as transducer which generates a signal (voltage) as a function of pressure imposed. However, performance of pressure sensor can be influenced to environment factors such as fluid density, atmospheric pressure, and also disturbance[3]. Pressure transducer can be classified based on type of pressure measured and their purposes as shown in the table 2.3.

Table 2.3: Type of pressure sensor and description [3]

Type of Pressure Sensor	**Description**
Absolute pressure sensor	• A sensor that measure pressure relative to perfect vacuum
Gauge pressure sensor	• A sensor that measure pressure relative to atmospheric pressure
Vacuum pressure sensor	• A sensor that measure pressure below atmospheric pressure which can be categorized into two: 1) Negative gauge pressure –Measure difference between low pressure and atmospheric pressure 2) Absolute pressure –Measure of low pressure relative to perfect vacuum
Differential pressure sensor	• A sensor that measure difference between two pressure

In this project, pressure sensor is used to measure the depth level of the ballast tank. Besides that, pressure sensor is used as a feedback of the system which used to compare between output responses with desired input set. There are many types of analog pressure sensor such as piezoresistive strain gauge, capacitive, electromagnetic, piezoelectric, optical and potentiometric [3]. However, there are two types of pressure sensor that are suitable to be implement in water application which are piezoresistive strain gauge and capacitive pressure sensor. This is because both pressure sensor capable to measure the differential pressure in between two pressure depths. Table 2.4 shows comparison of these two types of pressure sensor.

Table 2.4: Comparison between piezoresistive strain gauge and capacitive sensor[3]

Type of sensor	**Advantage**	**Disadvantage**	**Design**
Piezoresistive strain gauge	• High sensitivity (>10mV/V) • High capability to detect the changes of pressure without signal hysteresis until its limit	• The offset is difference for each pressure sensor and has a large value • Has offset toward temperature	
Capacitive	• High level of output • Good in linearity toward pressure changes • Long term stability	• Has limited mechanical motion • Low accuracy of pressure sensing	

By comparison, piezoresistive strain gauge will be selected in this project because it has high sensitivity with changes of pressure. MPX series is a type of piezoresistive strain gauge that is suitable to be applied to ballast tank due to small design and high reliability. Figure 2.7 and Figure 2.8 show the pressure pin connection and circuit diagram for MPX2450GP. While, Table 2.5 and table 2.6 shows the operating characteristic of the MPX series sensor in specific.

Pin Number			
1	V out	4	N/C
2	Gnd	5	N/C
3	V ss	6	N/C

Figure 2.7: Pressure Sensor pin connection[3]

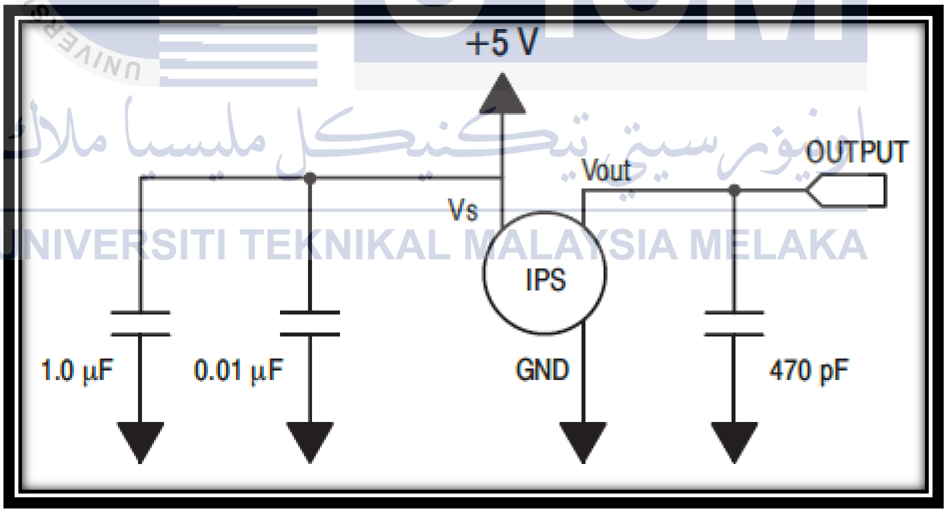


Figure 2.8: Circuit diagram for MPX4250GP [3]

Table 2.5: Offering information of MPX pressure sensor[3]

		#No. Port			Pressure Type		
Device Name	**Package Options**	**None**	**Single**	**Dual**	**Gauge**	**Differential**	**Absolute**
MPX****AP	Tray		X				X
MPX****GP	Tray		X		X		
MPX****DP	Tray			X		X	

Table 2.6: Operating characteristic of MPX pressure sensor[3]

Characteristic	**Symbol**	**Min**	**Typ**	**Max**	**Unit**
Pressure Range (1)	POP	0	-	250	kPa
Supply Voltage (2)	Vs	4.85	5.1	5.35	Vdc
Supply Current	Io	-	7.0	10	mAdc
Minimum Pressure Offset (3) (0 to 85oC) @ Vs = 5.1 Volts	VOFF	0.139	0.204	0.269	Vdc
Full Scale Output (4) (0 to 85oC) @ Vs = 5.1 Volts	VFSO	-	4.909	4.974	Vdc
Full Scale Span (5) (0 to 85oC) @ Vs = 5.1 Volts	VFSS	-	4.705	-	Vdc
Accuracy (6) (0 to 85oC)	-	-	-	±1.4	%VFSS
Sensitivity	$\Delta V \Delta P$	-	18.8	-	mVkPa
Respond Time (7)	tR	-	1.0	-	msec

2.6 Stepper Motor

Stepper motor is a synchronous motor with magnetic field electronically switched to rotate armature magnet around. and it also converts digital pulse into mechanical shaft rotation [9]. When a digital pulse is applied, stepper motor will rotates in a specific number of degrees. A stepper motor consists of three basic elements which are Indexer (Controller), Driver (Amplifier), and step motor as shown in Figure 2.9.

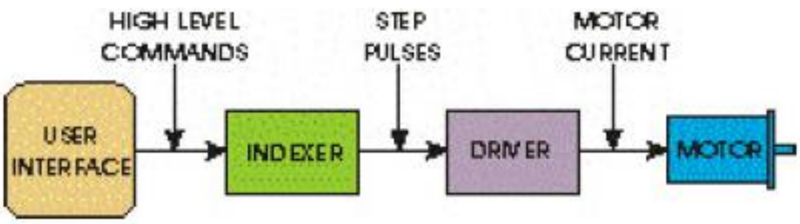


Figure 2.9: Basic elements of stepper motor [9]

There are many advantages of using stepper motor such as low cost, high reliability, high torque, rugged construction that operate in almost environment [9]. However, stepper motor also has main disadvantages which is resonance effect often exhibited at low speeds and decreasing torque when speed is increased [9]. In this project, stepper motor is chosen compare to DC motor. This is because of stepper motor using digital pulse and this can control rotation of shaft at specific degree and more accurate. Thus, this can be applied to movable piston to pump water in and out more accurate in order to control buoyancy at certain depth. Besides that, stepper motor has high torque with is necessary for this project that can pull water in and out at high water pressure. Stepper motor from model CRK PK566NAW (5-phase) is used in this project.

2.7 Microcontroller

Microcontroller used in this project is Arduino UNO as shown in Figure 2.10. Arduino is a tool for making computers that can sense and control more of physical world. Besides that, Arduino is open-source which means hardware is reasonably priced and development software is free [10]. Arduino can be used to develop interactive objects such as taking input from different switch or sensor, controlling many lights, motor, and other physical output. In this project, Arduino is chosen over other microcontroller because of some advantages such as:-

i) Inexpensive
ii) Cross-platform
iii) Simple, clear programming environment
iv) Open source and extensible software
v) Open source and extensible hardware

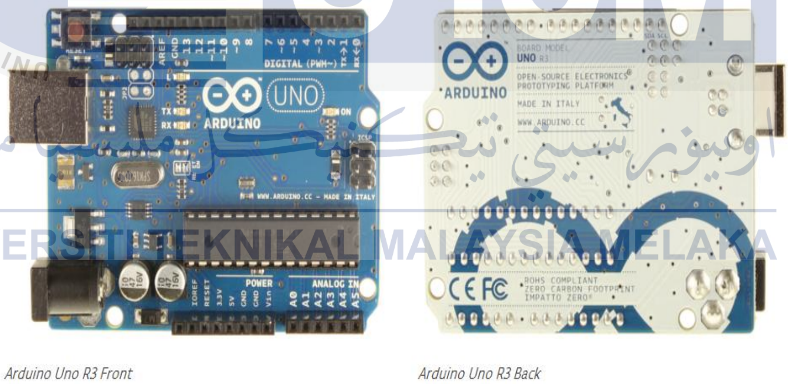


Figure 2.10: Arduino's UNO [10]

2.8 Depth Control Methods

Many researches that have been done by many peoples to control depth level using buoyancy concept. Main purpose is to reduce the high power consumed when using thruster. This part will focus on the control method that is use by others thesis to increase the performance of ROV.

2.8.1 Dynamic Leveling Control of a Wireless Self-Balancing ROV Using Fuzzy Logic Controller

The aim of this thesis is to design and develop a wireless self-balancing buoyancy system of a mini ROV using fuzzy logic controller [2]. A small hole has been made at the top of the mini ROV. The purpose is to maintain atmospheric pressure inside mini ROV when motor pump water in and out. However, this design has limitation where the ROV can only immersed in water. Figure 2.11 and Figure 2.12 show the Mini ROV physical construction and components of the fuzzy logic controller respectively.

Figure 2.11: Mini ROV physical construction [2]

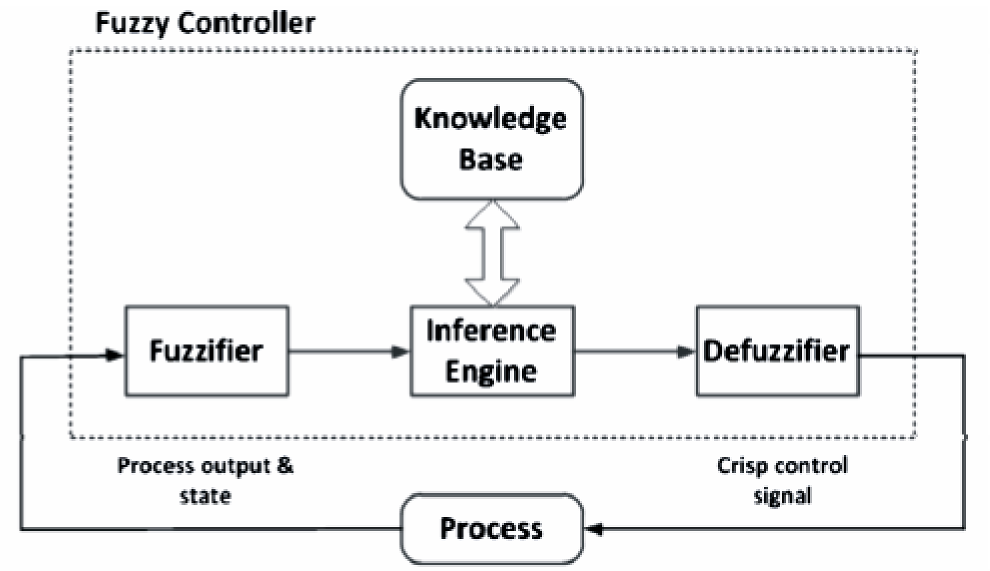


Figure 2.12: Component of the fuzzy logic controller [2]

The input for fuzzy controller is either mini ROV will submerge or surface, while the output is the time reference for DC pump to operate. A liquid level sensor is use as feedback to the controller. This thesis uses the MATLAB Simulink as the software development. Figure 2.13 shows the simulated response of the mini ROV without any controller.

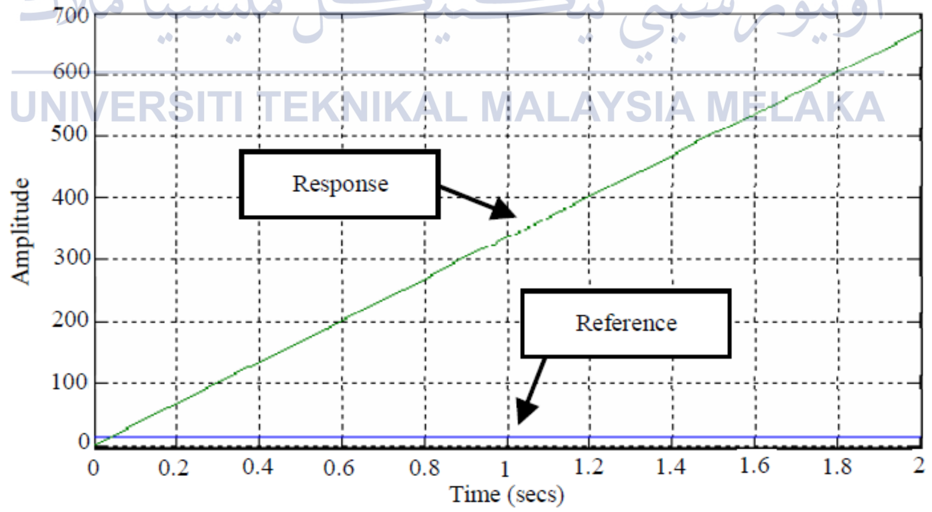


Figure 2.13: A mini ROV open loop response [2]

From the observation, the response is extremely unstable where it cannot reach the set point. In other to make the system stable, the fuzzy logic control is applied to the system. Figure 2.14 shows the simulated response that has been improving after use this controller.

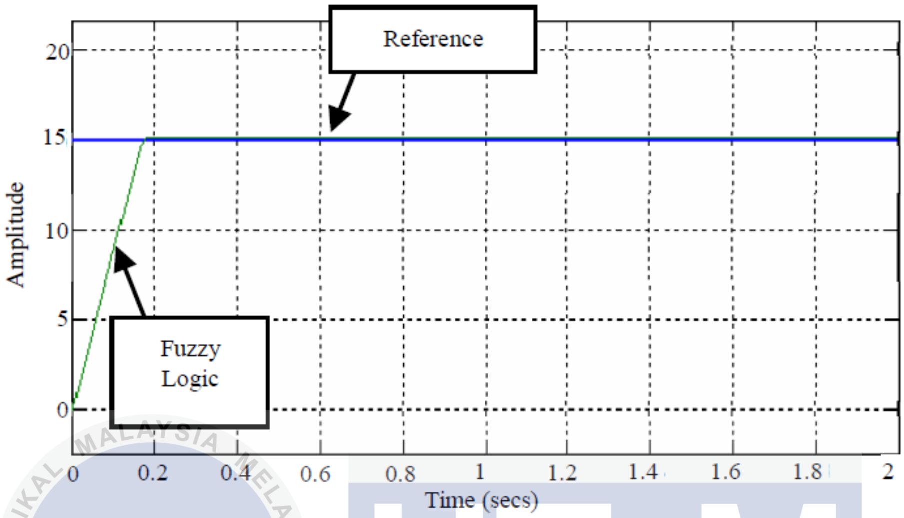


Figure 2.14: Fuzzy logic control system response [2]

Besides that, this thesis also has make the comparison with others controller such as PD and PID controller. Figure 2.15 and figure 2.16 show the simulated response for the PD and PID respectively.

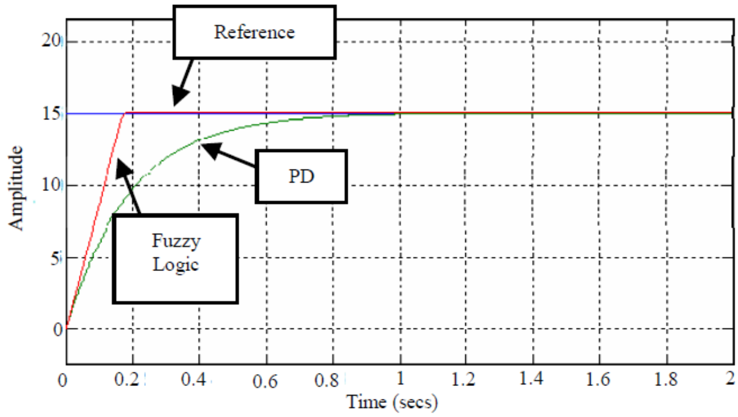


Figure 2.15: Comparison between fuzzy logic control and PD control system [2]

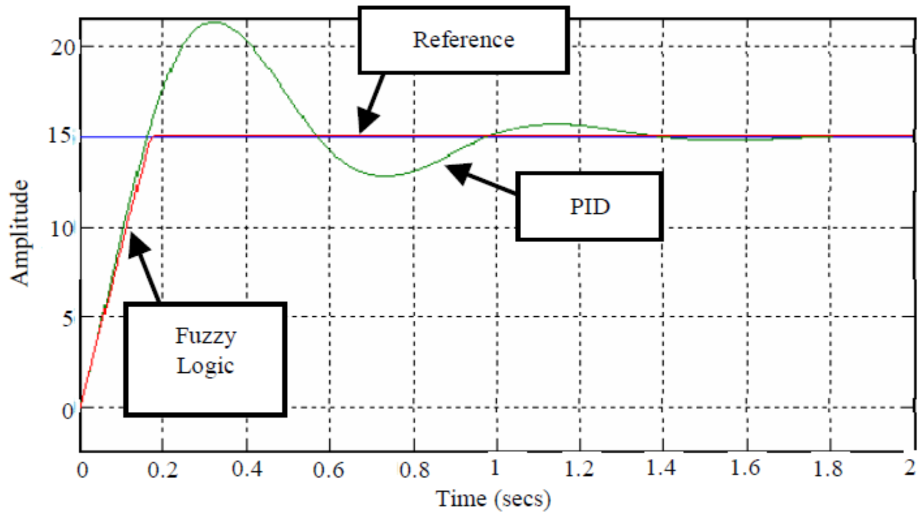


Figure 2.16: Comparison between fuzzy logic control and PID control system [2]

Thus, based on simulation and analysis result, fuzzy logic controller give a faster performance to reach the set point compared to PD and PID controller [2]. However, PID controller produce an overshoot at the output response before it reach the set point.

2.8.2 Depth and Trim Control of an AUV

The aim of this project is to investigate an alternative method to trim and depth control in order to minimize power consumption. The method chosen was to alter buoyancy of the vessel. This method performs for minimal weight calibration, and reduces power consumptions [11]. The Arduino UNO is chosen for this project as a depth control system. Pressure sensor performs as feedback to drive the actuator to change the depth of AUV. In other to make sure the vessel can maintain at desired depth, a PID controller is applied in this project to achieve the maximum response [11]. Figure 2.17 shows the design model of Depth and Trim Control.

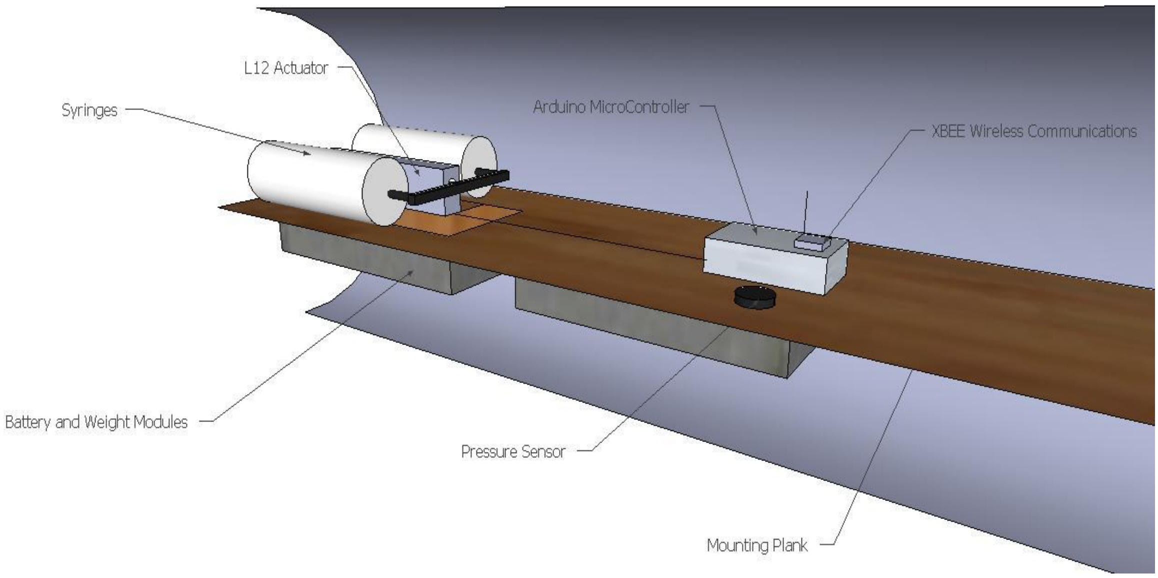
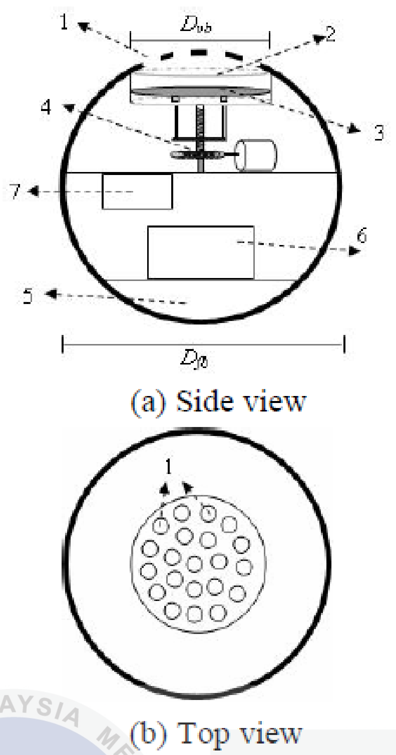


Figure 2.17: The design model of Depth and Trim Control of an AUV [11]

2.8.3 Development of Variable Ballast Mechanism for Depth Positioning of Spherical URV

Variable ballast is used to control the buoyancy of the body in Underwater Robotic Vehicle (URV) system. Besides that, a motion actuator in vertical plane can be performed also by using variable ballast [8]. Main advantage of using variable ballast is efficient in power usage. Hydrostatic force is depend on the depth position, which means power needed to change weight of URV is higher in deep water compare than shallow water that needed less power [8]. However, variable ballast seen that the system is nonlinear. Therefore, this thesis suggests a control system for a depth positioning need to be added to the URV. Figure 2.18 shows the shape of spherical URV.



1. holes for the way of water enter and exit the tank.
2. variable ballast tank.
3. movable plate.
4. power screw and worm gear
5. fixed ballast.
6. battery.
7. cpu and electronics components.

Figure 2.18: Shape of spherical URV and its parts [8]

2.8.4 Development, Depth Control and Stability Analysis of an Underwater Remotely Operated Vehicle (ROV)

This thesis presents two different control schemes for depth regulation and their performances are compared. First is a unit feedback control system, and second control scheme based on a PID controller. These both controllers will be analyzed which one is the best controller that can keep amplitude of overshoot in response drastically limited to depth set-point change, while keeping the response time reasonably contained [12]. The pressure sensor is chosen to obtain the depth of the ROV. Then, the depth obtain will be compared with the set-point, so this make the close loop.

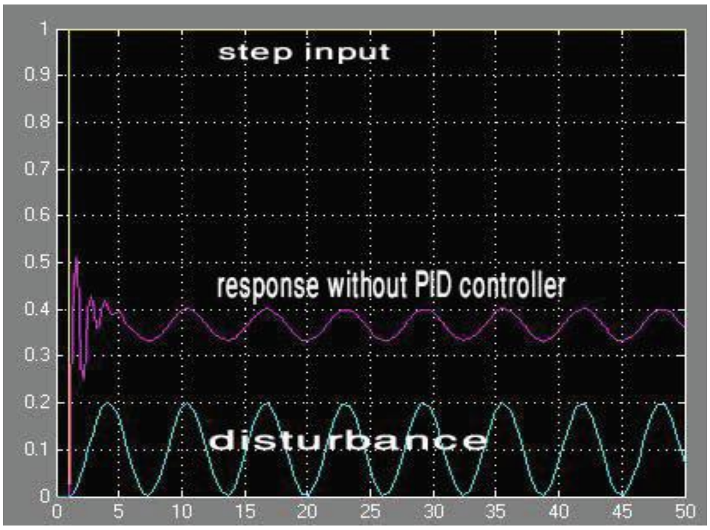


Figure 2.19: Step response for closed-loop feedback system [12]

Based on Figure 2.19, the output response is not stable which have overshoot and steady-state error. These overshoot and steady-state error can be reduced by adopt a PID controller [12]. Figure 2.20 shows the output response for a PID control system that has a better performance.

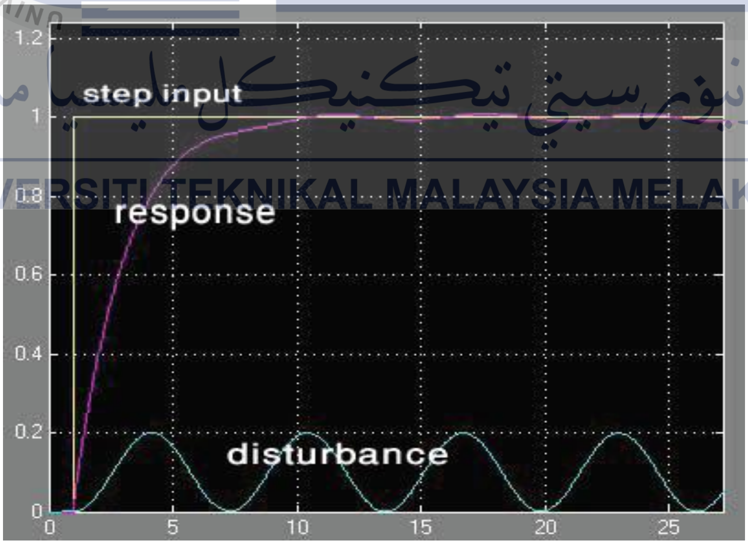


Figure 2.20: Step response for PID control system [12]

2.8.5 Design and Control of Autonomous Underwater Vehicle using Variable Buoyancy System

Figure 2.21 shows the construction of the AUV. This thesis want to overcome high power consume operated by power thrust of autonomous underwater vehicle (AUV) when maintain at a certain depth. In order to overcome this problem, this thesis has introduced variable buoyancy system. Pressure sensor is chosen as a feedback system. The signal from pressure sensor is used to maintain the AUV at a certain depth. Electronic control is used in this thesis as the control system. This controller will operate at 5v dc and achieve desire function by comparing stored data on the memory with it stores the current activity [4]. This thesis can able to meet its required specification, objective and mission. However, the AUV is unbalance when there are the small changes in weight. Thus, PID controller is suggesting in the future making the AUV to be more stability [4].

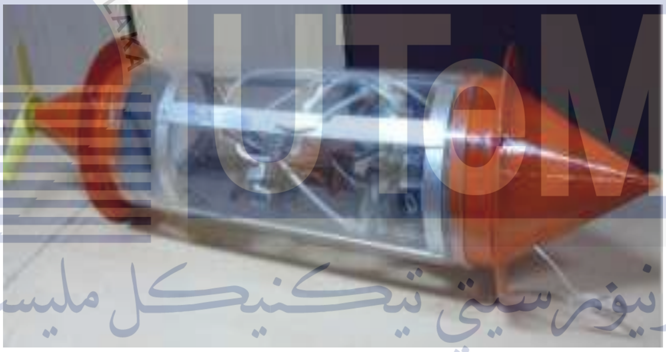


Figure 2.21: VBS based AUV [4]

2.9 Conclusion of Control Method

Based on research of other project around has proved that PID controller is suitable and best controller in order to control depth of ROV at certain depth. Even modern controller likes Fuzzy logic, neural network control and adaptive control show the better performance in controlling depth, but this controller is complex and more suitable to be apply at the deep sea up to 6000m [5]. Since this project only operate on shallow water, simple controller like PID is more practical to be implemented.

Block diagram in Figure 2.22 shows a close loop control system for ballast tank with the additional of PID controller.

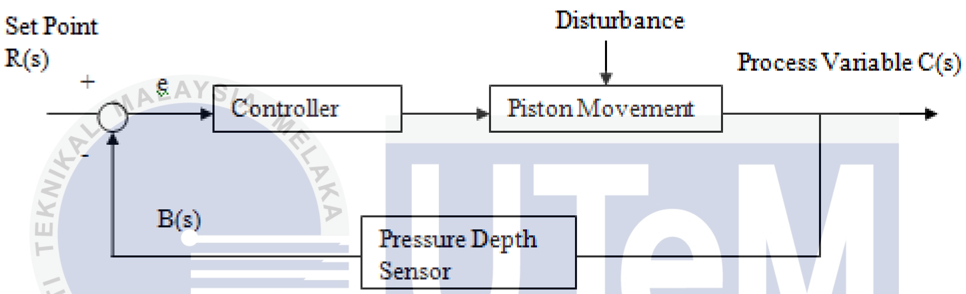


Figure 2.22: Block diagram of close loop system for ballast tank

Basically, the set point R(s) is declared to desire depth of ballast tank that want to be maintained. This set point can be done in the Arduino's microcontroller in term of voltage form. Pressure sensor (MPX4250GP) is used to detect the actual pressure of ballast tank and convert to the voltage based on changing of depth. Output voltage from pressure sensor is increased when the depth level is increased. Then, this output voltage will be compared with the desired set point. The difference between the desired set point R(s) and the pressure sensor output voltage B(s) is called as voltage error, e as shown in equation (2.5) below;

$$e = R(s) - B(s) \tag{2.5}$$

Then, this voltage error will be sent to controller for improvement, thus can control the piston movement of ballast tank near to desired depth.

$$Pout = [R(s)-B(s)]*controller \tag{2.6}$$

Based on the equation 2.5, when value of voltage error is positive, then piston movement will retract (pump in water). The positive of voltage error indicate that actual depth still not achieved the desired depth. While, when voltage error is negative indicate that actual depth of the ballast tank over from desired depth. Then, piston movement will expand to pump out water. Lastly, if voltage error is zero indicates that ballast tank already in desired set point. Thus, piston movement will stop move to maintain at this position. Figure 2.23 illustrates the position of ballast tank at different voltage error.

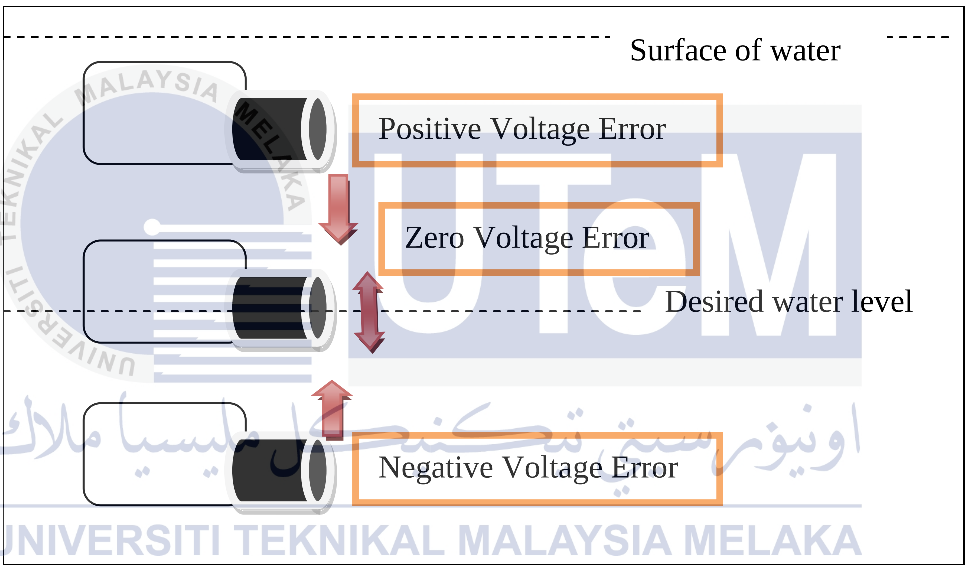


Figure 2.23: The position of the ballast tank based on the condition of voltage error

CHAPTER 3

METHODOLOGY

3.0 Introduction

Methodology is part where method and step that need to clearly determine to make sure this project is complete with successfully. The mechanical design will focus on the construction of the ballast tank that can move the piston to control the water ratio. Next, PID controller will be applied to ballast tank system in order to improve performance. Lastly, experiment will be conducted to obtain performance of the ballast tank for open loop system and close loop system. Additional experiment will be conducted for closed loop with applied of disturbance. Then, the algorithm system will be compared with the system control level from bottom.

3.1 Experimental Procedure

There are several steps in order to determine the Underwater Vehicle Buoyancy Control from the Surface.

3.1.1 Mechanical Design for Ballast Tank

This section will focus on the process to develop the ballast tank. Figure 3.1 shows the flow chart to design the ballast tank. List part of the piston ballast tank can be referred to Appendix B.

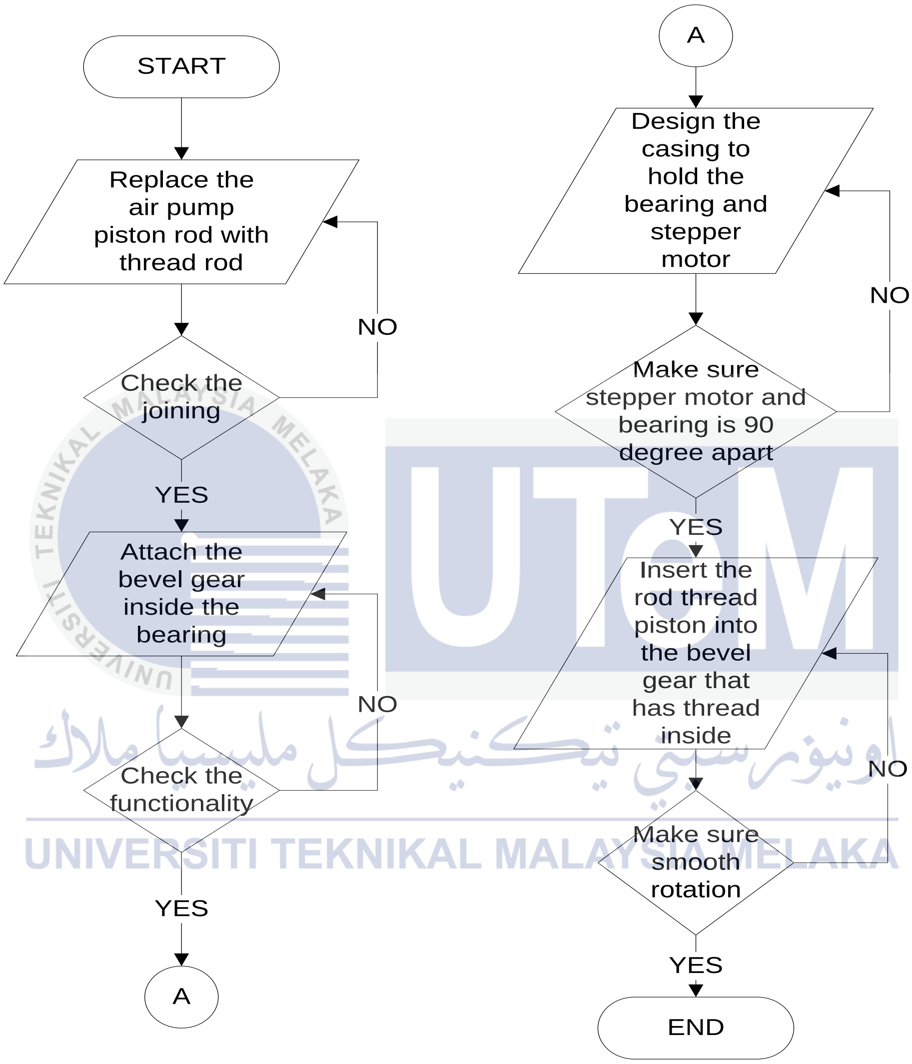


Figure 3.1: Flow chart for ballast tank design

The complete assemble mechanical part of ballast tank as shown in Figure 3.2. The ballast tank used is bigger than previous final year student in order to maintain level at higher depth. Table 3.1 and Table 3.2 shows comparison in term of size and volume for the current ballast tank design with ballast tank design by previous final year student respectively. Based on comparison, the current ballast tank shows much bigger volume compared to previous ballast tank either for 1^{st} design or 2^{nd} design.

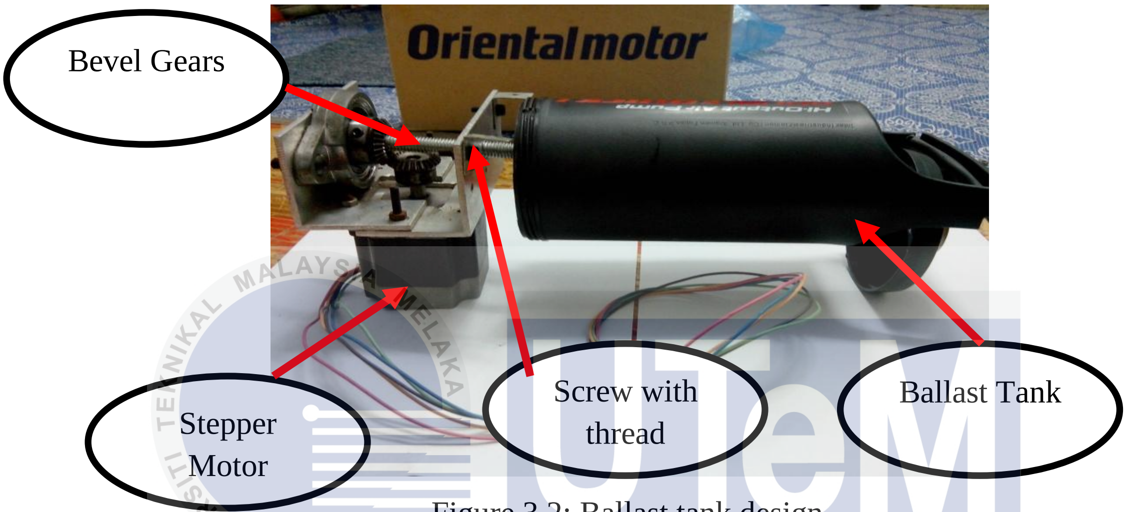
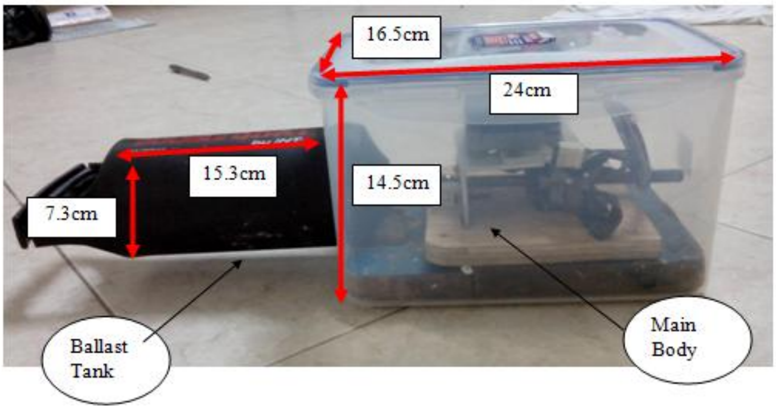


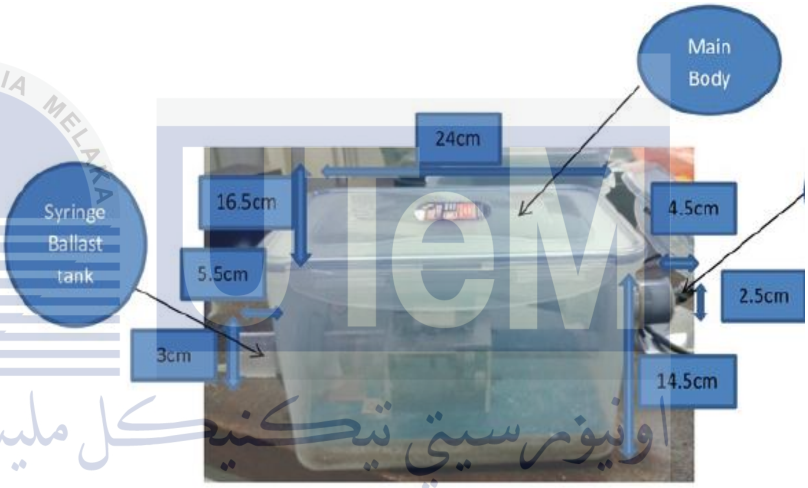
Figure 3.2: Ballast tank design

Table 3.1: Size comparison of the current ballast tank with the previous ballast tank

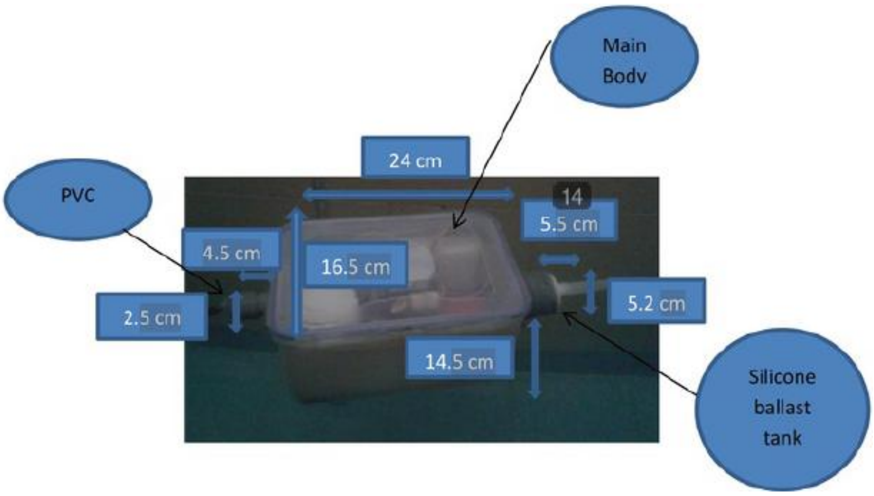
<table>
<tr><th>Type</th><th>Design</th></tr>
<tr><td>Current ballast tank</td><td>


</td></tr>
<tr><td>Previous ballast tank (by past year final student)</td><td>

- 1st design [5]



- 2nd design [5]



</td></tr>
</table>

Table 3.2: Comparison in term of volume

Type	**Volume (cm^3)**
Current ballast tank	640.45
Previous ballast tank (by past year final student)	➢ 1st design = 38.88 ➢ 2nd design = 116.82

The complete process for mechanical design can be seen at the Appendix C. After that, piston ballast tank needs to be test in order to make sure it meets requirement and safety. Therefore, manually test is to make sure that the piston ballast tank can pump water in and water out smoothly, and also can handle with high water pressure.

Next, Figure 3.3 shows the wiring part for this project. The wiring part includes such as power supply 24V, the motor driver, and Arduino UNO. The programming will be burn in Arduino's UNO microcontroller in order to control the pumping sequence of piston ballast tank.

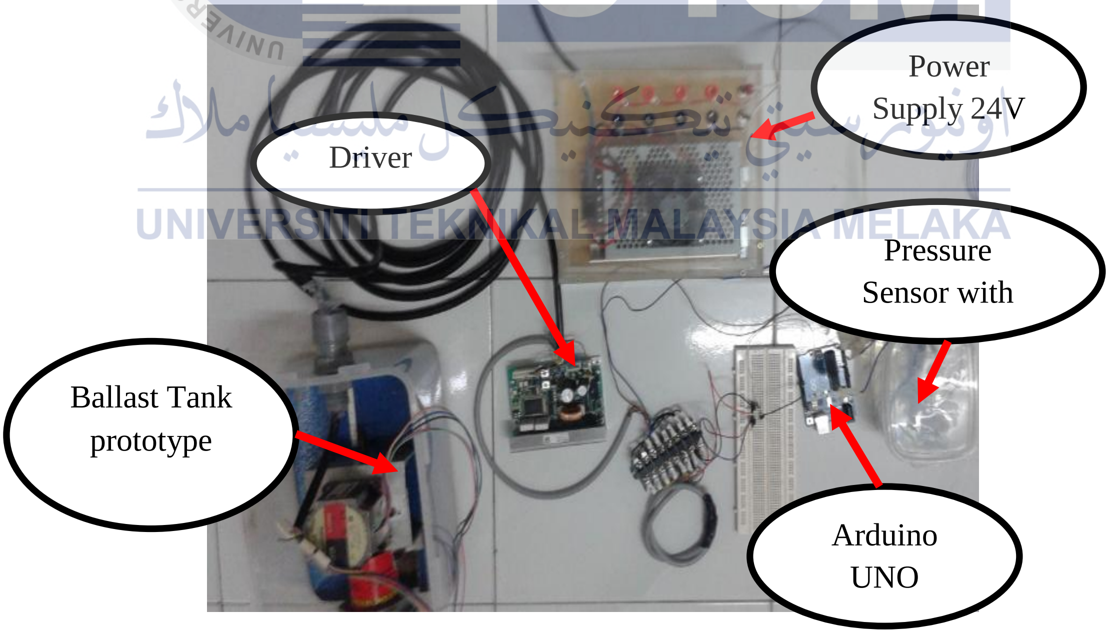


Figure 3.3: Wiring part

3.1.2 Weight Estimation Calculation

This section will focus on calculation of weight estimation that needs to be applied to the ballast tank. Calculation is used to estimate the external weight that needs to be applied in order to make the ballast tank slightly submerge. Table 3.3 shows the weight estimation for ballast tank. Detailed calculation in order to obtain the tabulated result in Table 3.3 is presented in Appendix D.

Table 3.3: Weight estimation for ballast tank

Type	**Weight (N)**
Main body	26.89
Ballast tank	3.34
Total	30.23

So the estimate weight to design ballast tank prototype to float slightly at water level is 3.08kg. Later, the weight estimation calculation will be compared to the real external weight applied to ballast tank that covered in Experiment 1. The comparison is used in order to prove the theoretical.

3.1.3 Experiment 1: Buoyancy of the Ballast Tank

The purpose of this experiment is to identify how heavy is an external weight needs to be put for the final ballast tank prototype design. Figure 3.4 shows the placement of external weight on ballast tank. In this experiment, the bar steel is used as an external weight where the weight for each bar steel is around 0.5kg. The external weight is added one by one (from 0.5kg until 3.5kg with 0.5kg increment) to get the actual weight that that can change state of the buoyancy in positive, neutral or negative buoyancy. The data for each weight vs buoyancy level is collected and then compared with the result from calculation.

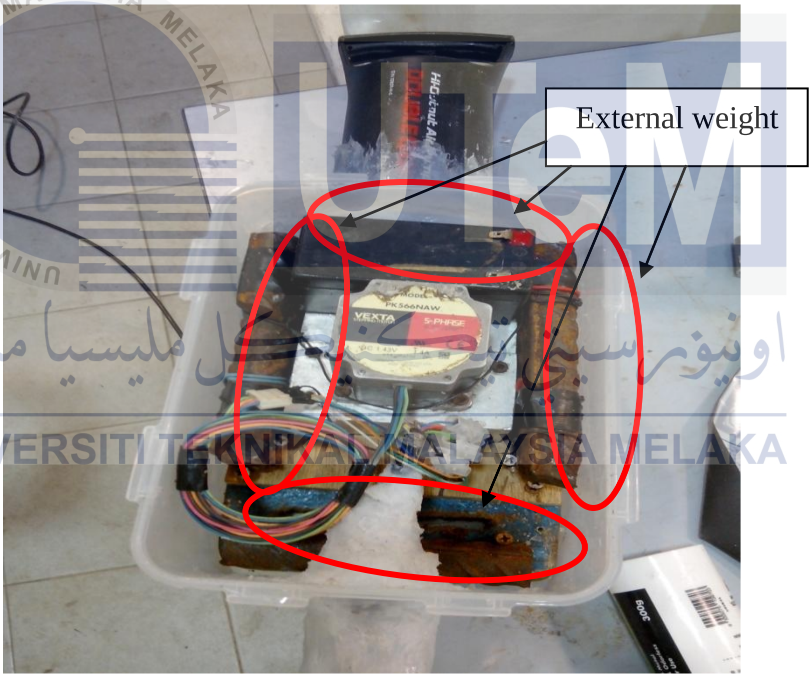


Figure 3.4: Placement of an external weight

3.1.4 Experiment 2: Characteristic of the Pressure Sensor

This experiment is conducted with the aid of pressure sensor (MPX4250GP). Figure 3.5 shows the placement of the pressure sensor inside the underwater lab pool. The output parameter measured by pressure sensor at different depth (from 0cm until 110cm with 10cm increment) is then converted to voltage. The output voltage can directly converted by using command in Arduino's microcontroller as shown below:

```
sensorValue=analogRead(A0);

voltage=0.0052*sensorValue;
```

Next, the output voltage produced can be measured from multimeter or Arduino serial monitoring. The data for each output voltage vs depth level is collected to obtain the relationship. The conversion from the pressure sensor unit (kPa) to voltage is essential as an input set (setpoint) for the next experiment in order to make the ballast tank maintain at a certain depth.

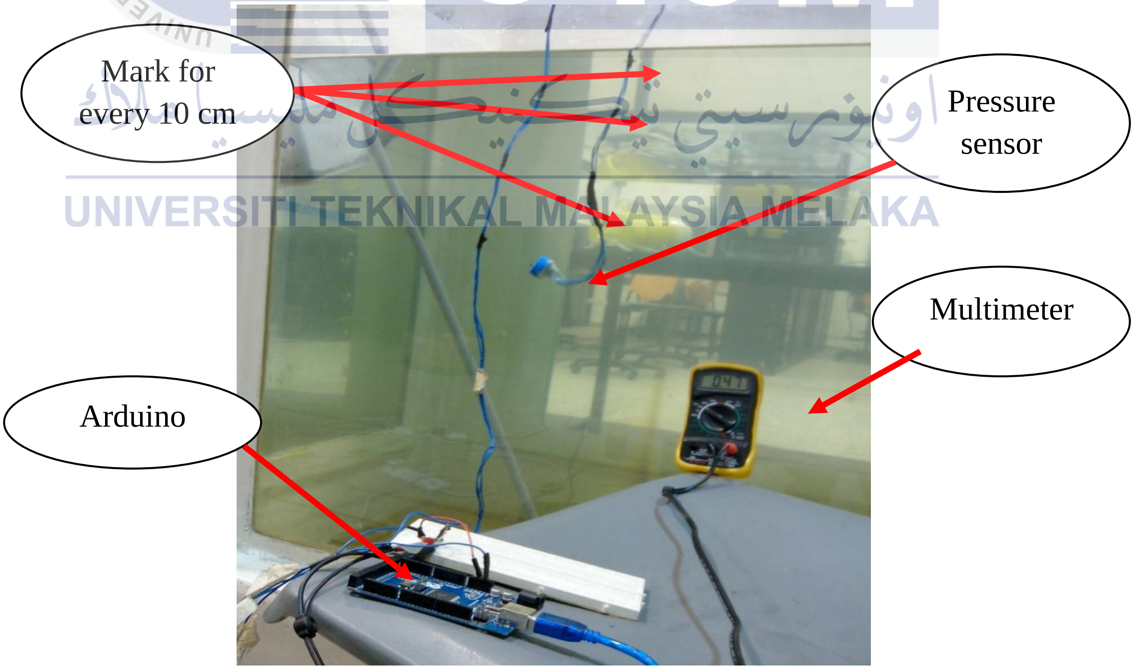


Figure 3.5: Placement of pressure sensor

3.1.5 Experiment 3: Manually Control Depth Level for Ballast Tank

The aim of this experiment is to determine the relationship between the movements of piston ballast tank with the depth water level. The movement of piston is controlled manually with the aid of Arduino and stepper motor installation in the ballast tank itself. In order to make the piston moves in forward or reverse direction, a driver switch that consists of polarity is used. The piston ballast tank will be move around 77mm (about 106s) in order to pump water in. After that, the stepper motor will be OFF and delay 5s is applied. The purpose of applying delay is to observe the movement of the ballast tank either it will directly stop or will continue move for certain distance. After 5s, the stepper motor will be ON back to pump out in order to rise back. After piston ballast tank move about 77mm, then the stepper motor will be OFF and again the delay 5s is applied for the same purpose. This process will be repeated for twice.

However, this experiment is done in open loop condition without considering any feedback system. This experiment is important to obtain data for the transfer function using System Identification as mentioned in section 3.1.6 later. The layout diagram for this experiment is shown in the Figure 3.6.

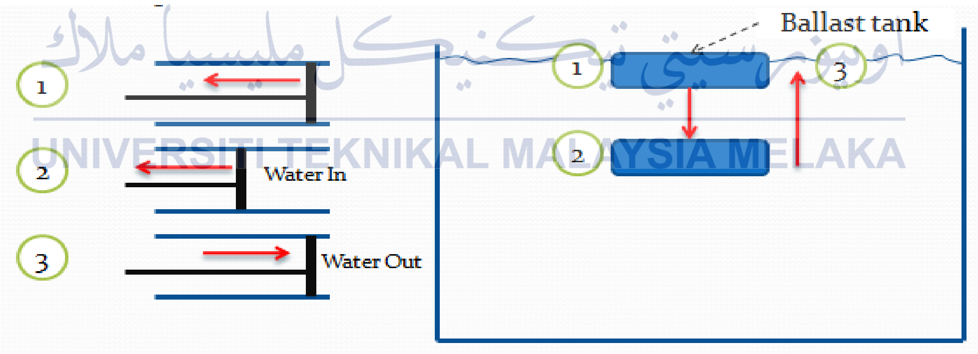


Figure 3.6: The relationship between the movements of the piston ballast tank with the water depth level

3.1.6 Obtaining transfer function for the ballast tank

This part will focus on how to get the transfer function for the ballast tank prototype. System Identification is used to get the transfer function based on the experiment 3. The transfer function obtained from System Identification is shown in equation (3.1) below. All the process to obtain the transfer function can be referred to Appendix G.

$$Gs\_tf = \frac{0.06818s+0.9343}{s^2+5.971s+12.5} \quad (3.1)$$

Equation (3.1) shows an open loop transfer function for a second order system. This system having a step input function. Based on the transfer function obtained in equation (3.1), a block diagram for open loop system is constructed to obtain the output response as shown in Figure 3.7.

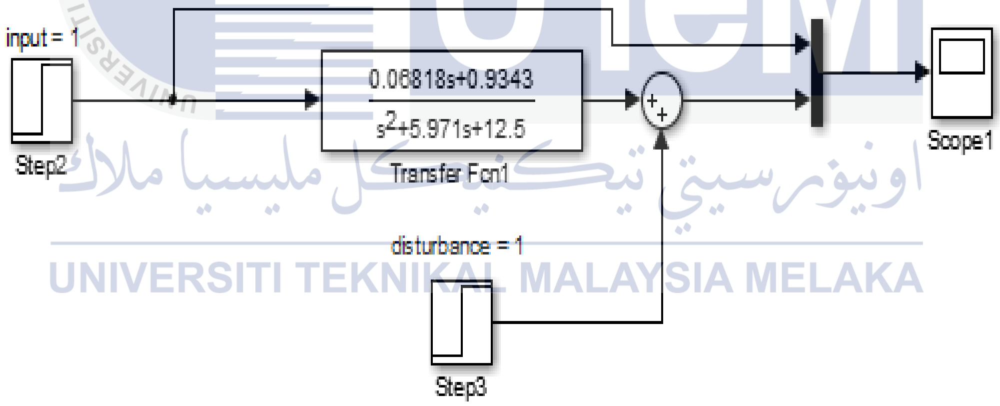


Figure 3.7: Block diagram for open loop system

3.2 Controller Designation

PID controller is design to improve the output performance of the open loop system. The PID tuning method is used by manually tune value for Kp, Ki, and Kd until achieved desired performance (refer to Appendix H). The priority that needs to be considered when manually tune is overshoot, where output response must less than 6.5%. Next, priorities are rise time and settling time, where both must less than 2s. After that, this PID controller will be applied to real hardware to see the real performance (rise time and settling time) of the ballast tank prototype (refer to Appendix J). PID controller can be performed in the simulink block diagram as shown in the Figure 3.8.

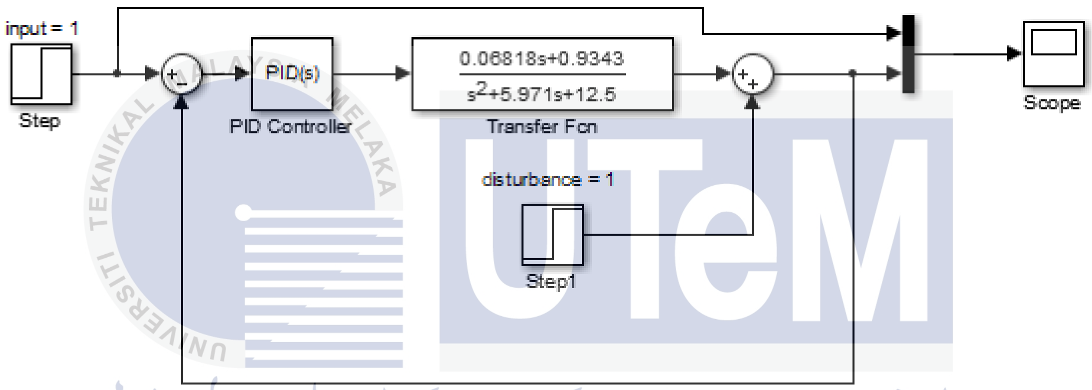


Figure 3.8: Block diagram for close loop system

3.3 Performance of the Ballast Tank

This section will focus on the testing of the ballast tank prototype performance. The ballast tank prototype will be tested on the capability to maintain at various depths, and this test will do for open loop system and closed loop system (with PID controller). Moreover, the closed loop system also will be tested with applied of disturbance. All of this test will be conducted in Experiment 4. After that, the algorithm system of the ballast tank will be compared between the system control level from surface and the system control level from bottom.

3.3.1 Experiment 4: Performance (Rise Time and Settling Time) of the Ballast Tank Prototype

This experiment will investigate the performance of the ballast tank prototype in two conditions, which is in the open loop system and close loop system. The ballast tank will focus on the capability to maintain at every 10cm increment of depth level and can rise back to initial position. Then, the performance of open loop system and closed loop system will be based on the capability to maintain and rise back. After that, the limitation of this project is identified based on the maximum depth that the ballast tank cannot able to maintain or cannot rise back after maintain at certain level.

Besides that, this section also will cover on the test for closed loop with applied of disturbance. The experiment was conducted to see the behavior of the ballast tank to overcome the disturbance applied at different revolution per minute (rpm) of stepper motor. The rpm used is between 300 rpm and 200 rpm. Moreover, the depth level is fixed for maintaining at 20 cm. The disturbance used is screw and weight is 20g each. Figure 3.9 and Figure 3.10 show the placement of the screw at the top of the ballast tank and the layout effect of disturbance applied. After the ballast tank is stable, one screw will be dropped to the ballast tank and movement of the ballast tank will be record. Another screw will be dropped to the ballast tank if it capable to maintain back at 20cm. This process is continued until the ballast tank cannot handle the applied disturbance either cannot maintain or rise back.

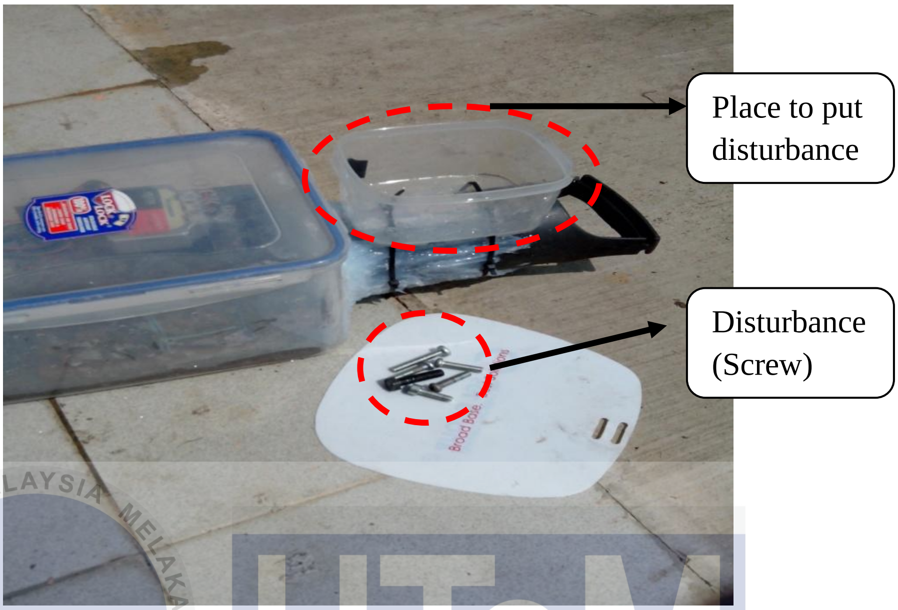


Figure 3.9: Ballast tank and disturbance

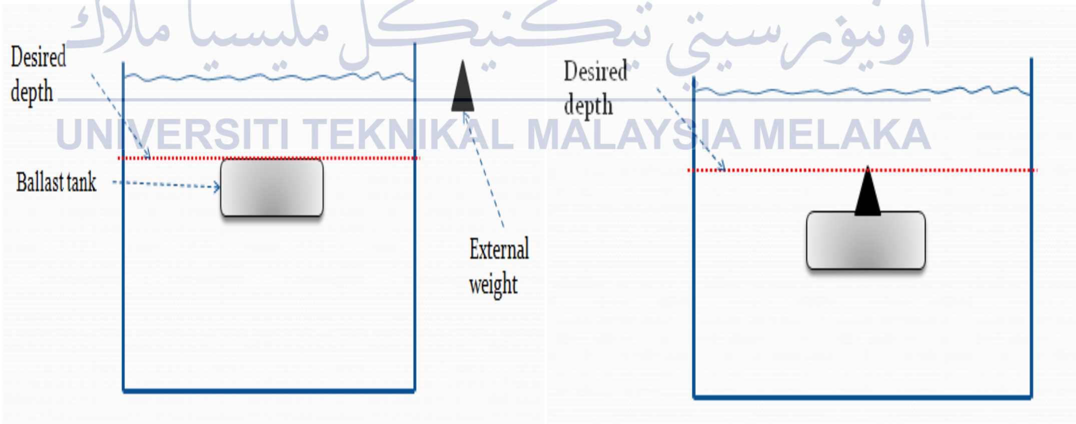


Figure 3.10: Effect after disturbance is applied

3.3.2 Compare the Algorithm System of the Ballast Tank

The aim of this section is to compare the algorithm system between the system control level from surface with the system control level from bottom. Both algorithms will be compared for the open loop system, closed loop system, and with applied of disturbance. The algorithm will focus on the performance (rise time and settling time), similarity, differences and limitation.

3.4 Conclusion

There are three main sections in this chapter that is conducted in order to achieve the objectives of this project, which are the mechanical design of the ballast tank, controller designation, and performance of the ballast tank. Then, every experiment is repeated in order to validate the data.

CHAPTER 4

RESULT AND ANALYSIS

4.0 Introduction

This chapter will be analyzed the result based on the experiment that has been conducted in the methodology. The data are collected and presented in the form of graphs and the tables based on the result obtained through out all the experiments conducted.

4.1 The result for Buoyancy of Ballast Tank

Table 4.1 shows the data collected for Experiment 1 which is buoyancy of ballast tank on the methodology process.

Table 4.1 Buoyancy observation for ballast tank

External Weight (kg)	Positive Buoyancy	Neutral Buoyancy	Negative Buoyancy
0.50	✓	-	-
1.00	✓	-	-
1.50	✓	-	-
2.00	✓	-	-
2.50	✓	-	-
3.00	-	✓	-
3.50	-	-	✓

By referring to the Table 4.1, the ballast tank is maintained at positive buoyancy when the external weight is applied until 2.50kg. When 3.00kg external weight is applied, the ballast tank starts change state to the neutral buoyancy. However, when 3.50kg external weight is applied the ballast tank becomes negative buoyancy.

In this experiment, the external weight at neutral buoyancy which is 3.00kg will be selected to implement in the final designing of the ballast tank. This is because at the neutral buoyancy the ballast tank will capable to submerge and rise back to surface. If the ballast tank is too positive buoyancy, the ballast tank will not submerge even though the piston is pump in water until maximum movement of the piston. While, if the ballast tank is negative buoyancy, the ballast tank will immediately submerge even though the piston still not pump water in yet. Therefore, the most practical to make the ballast tank is at neutral buoyancy.

From the weight estimation calculation using Archimedes principle, the amount of weight that need to make the ballast tank neutral buoyancy is 3.08kg. Thus, by comparing between the weight estimation calculation and the actual weight added are almost similar which only 0.08kg deviation. This shows that the Archimedes principle is very useful when designing device.

Besides that, the external weight used in this experiment is bar steel. This material is selected because it shows a better characteristic compare to other material such as wood or glass. In this experiment, the characteristic of material will be selected based on the density. Bar steel shows the higher density compared to other materials even it has a same size. The space inside the ballast tank is limited to add with bigger size of external weight. Thus, the material with higher density, but small size is required to suite with empty inside the ballast tank. Therefore, the bar steel is used as the external weight is this experiment.

Other than that, the placement of the external weight also very important in order to make sure that the ballast tank will stable for every sides in underwater. Figure 4.1 shows the stability of the ballast tank when the external weight 3.0kg is applied.

Figure 4.1: Stability of the ballast tank

4.2 The Result for Characteristic of the Pressure Sensor

Table 4.2 shows the output voltage from the pressure sensor at different depth level.

Table 4.2 Characteristic of the pressure sensor

Depth (cm)	Output Voltage (V), Trial 1	Output Voltage (V), Trial 2	Output Voltage (V), Trial 2	Average (v)
0	0.18	0.18	0.18	0.18
10	0.20	0.19	0.19	0.19
20	0.21	0.21	0.21	0.21
30	0.23	0.22	0.22	0.22
40	0.24	0.24	0.24	0.24
50	0.26	0.25	0.25	0.26
60	0.28	0.27	0.27	0.27
70	0.29	0.29	0.29	0.29
80	0.31	0.30	0.30	0.30
90	0.33	0.32	0.32	0.32
100	0.34	0.34	0.34	0.34
110	0.35	0.35	0.35	0.35

By referring to the Table 4.2, the output voltage of pressure sensor is tested for three trials at the same depth level. Then, the average output voltage for each depth level is calculated by using the equation (4.1) as below;

$$\text{Average voltage output (v)} = \frac{\Sigma v}{n} \qquad (4.1)$$

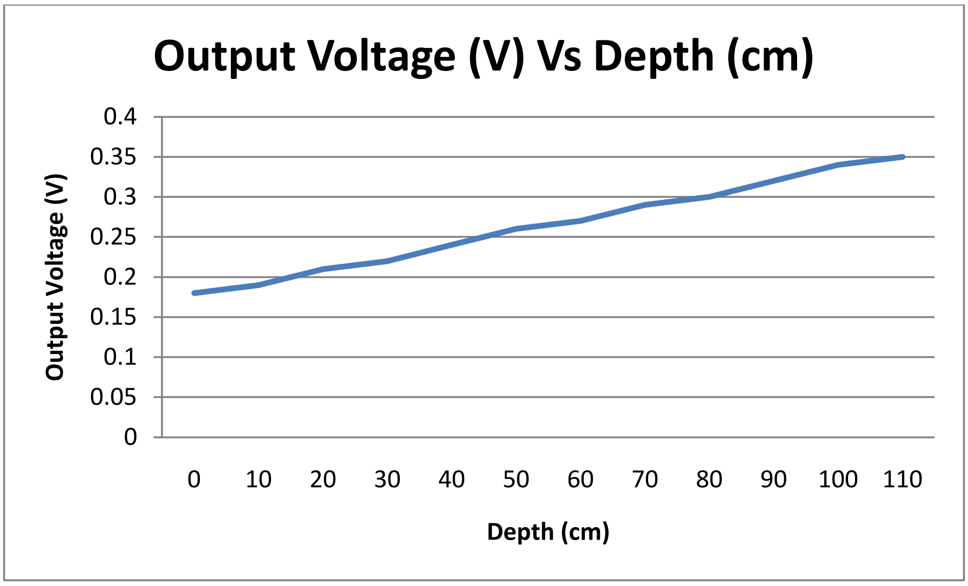


Figure 4.2: Graph of output voltage Vs depth level

Figure 4.2 shows the output voltage from the pressure sensor vs depth level. Based on the graph, the output voltage is proportional to the depth level. When the depth level is increased the pressure also will increase, thus the output voltage also will increase. This was proven the theory as stated in Equation (4.2) where the pressure is increased when the height (h) is increase;

$$P = \rho g h \tag{4.2}$$

Where:

P = Pressure, [Pa]

ρ =Density of water, [1000kg/m^3]

g = Gravitational force, [9.81 m^2/s]

h = Height [m]

Besides that, the pressure sensor still read the output voltage even the depth level is still at 0cm. This is due to the pressure from the atmospheric pressure which is at 1atm (101.325kPa). Moreover, the graph also shows that the output voltage will increase by 0.01V or 0.02V when the depth level is increased for every 10cm increment. However, this is only small variation about 0.01V and this is due to the sensitivity of the pressure sensor used is more than 10mV/V. Therefore, this output voltage of the pressure vs depth level still can be concluded as a valid data.

Lastly, the output voltage of pressure sensor can be obtained from the reading of multimeter or Arduino's serial monitoring. Then this output voltage is essential as an input set (setpoint) for the next experiment in order to make the ballast tank maintain at desired depth. Later, this input set will control the movement of the piston ballast tank either to pump water in or pump water out by comparing with the feedback voltage from the pressure sensor (actual depth).

4.3 The Result for Manually Control Depth Level for Ballast Tank

From the result obtained at Appendix F, the data is converted into a form graph as shown in Figure 4.3 and Figure 4.4 respectively.

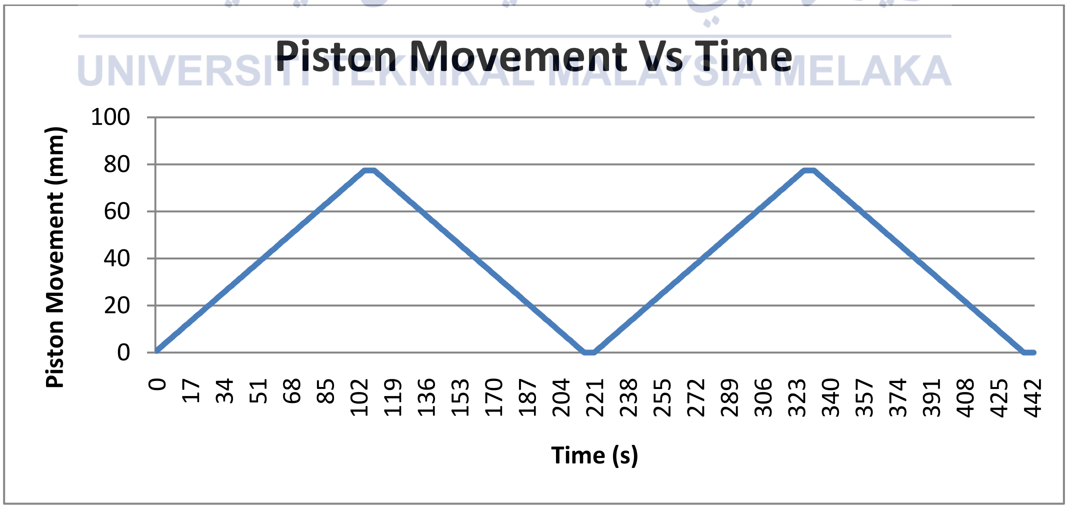


Figure 4.3: Graph of piston movement Vs time

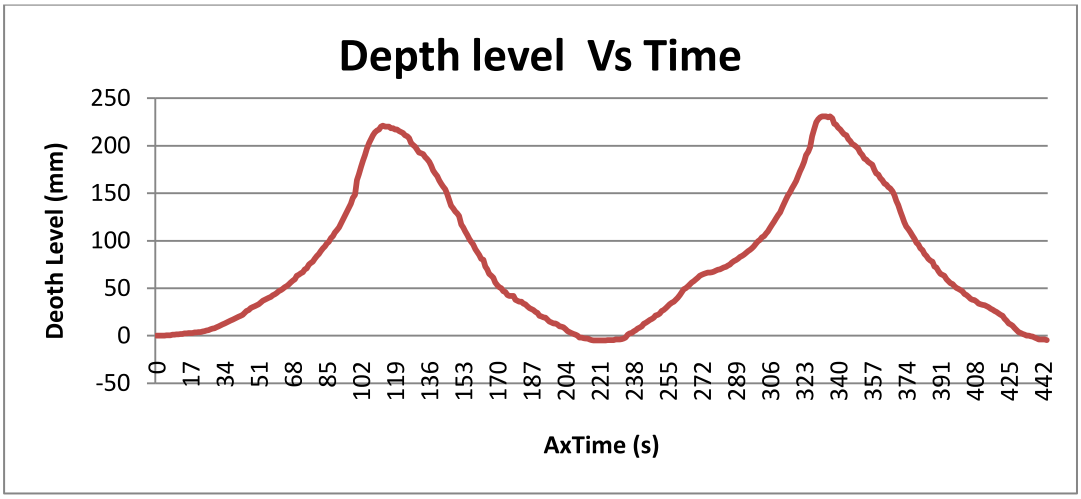
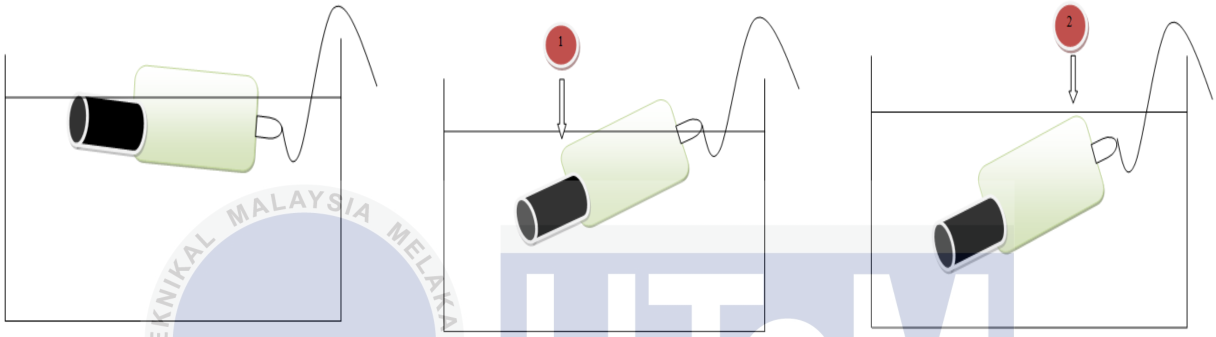


Figure 4.4: Graph of depth level Vs time

Based on the Figure 4.3, the piston ballast tank will pump water in until the piston movement equal to 77.38mm. This piston movement was taking about 106s to reach that point. After that, the piston is stop moving with a delay 5s before the piston is pump out water back. After the piston reach back to the initial condition, the piston will stop move and again a delay 5s applied. The purpose of applying delay is to observe the movement of the ballast tank either ballast tank will directly stop or will continue move for certain distance. This process will repeat for twice in order to validate the obtain data.

By referring to Figure 4.4 shows that the ballast tank remains unchanged until the piston movement equal to 2.92mm (4^{th} second). The reason is because the volume of water that pumps during this period is still in a small amount. After that, the depth level of ballast starts changes to 0.5mm when piston movement is 3.65mm (5^{th} second). However, this depth level again remains unchanged for the next 3s which is until piston movement equal 5.11mm. Same reason because the volume of water still is still not enough to make ballast tank change the depth. Other reason is because the pressure is still low and similar for this range of depth level. Therefore, at early 22s which is equal 16.06mm piston movement, the depth level will remain unchanged at least two or three second piston movement next after that due to small amount of water pump and low pressure.

Next, the depth level of ballast tank starts to change almost linearly with the respect of the piston movement. This is because the pressure of the water start to increase and force over the ballast tank. Thus, even a small volume water pump in at every second changes can change the depth level. However, at time 100s with is equal to 73mm piston movement, the depth level was change drastically from 148.5mm to 164mm. This happens because of the limitation of the hardware design as shown in the Figure 4.5 (a), Figure 4.5 (b), and Figure 4.5 (c).



(a) Initial position (b) First sliding happen c) Second sliding happen

Figure 4.5: Limitation of the Hardware (a) Initial position; (b) First sliding; (c) Second Sliding

So, based on the experiment conducted the ballast tank still continues to move when delay 5s is applied. This is because of the momentum of the ballast tank and the water pressure toward the ballast tank.

After that, the stepper motor is ON and piston ballast tank start to pump water out. However, the ballast tank still continues to submerge even though the piston is pump out water. This occurs at 112s and 113s where the ballast tank starts to pump out water. When 114s piston movement (equal to 75.19mm) pumps out water, then the ballast tank starts to rise. The ballast seems to maintain at same depth level position for the next two or three second because during this depth level the ballast tank needs to overcome the water pressure [8]. The small amount of water that has been pulled out cannot make the ballast tank to change the depth level. This happens until 120s where the ballast tank pulls out the water where equal to 68.62mm piston movement. After that, the ballast tank back to linearly rise which respect to the piston movement. However, at the piston movement equal to 5.11mm (210s) the ballast tank already reaches the initial position. While at the piston movement fully pushed, the depth level is at -4.5mm away from the set point. This is due to momentum of the ballast tank that is continued to move even the stepper motor is OFF. But, this momentum causes the ballast tank to move only small movement. Besides that, the ballast tank remains at the same depth level which is -5mm away from the initial starting point during the 5s delay. The reason for both situations is because of the water pressure is low compared to previous condition.

After that, when the ballast tank is submerge for the second time it seems that the final depth level reach is 217mm which is 14mm away from the first one. This is due to the limitation of the wire that connected between the stepper motor to the power supply. The wire used has effect on buoyancy, and when it moves will affect the depth level of the ballast tank. Lastly, the result from the Appendix F is used to obtain the transfer function by using System Identification in Matlab.

4.4 The Result for PID Tuning Method based on manually Tune

Table 4.3 shows the performance in term of rise time, settling time, and overshoot at different values of Kp, Ki, and Kd (refer to Appendix I).

Table 4.3: PID tuning method

No.	Kp	Ki	Kd	Rise Time, Tr	Settling Time, Ts	Overshoot, OS%	Final Value
1	3.73	19.21	-1.71	0.83s	3.21s	4.59	1
2	16.58	58.03	0.15	0.41s	1.7s	9.52	1
3	27.30	72.52	0.00	0.32s	1.46s	8.94	1
4	33.64	69.76	-0.63	0.30s	1.45s	7.69	1
5	35.66	75.80	-0.40	0.28s	1.39s	8.19	1
6	31.87	69.78	0.56	0.31s	1.43s	6.20	1
7	40.34	67.92	-1.03	0.27s	1.45s	6.88	1
8	42.48	73.49	-0.71	0.26s	1.38s	7.34	1
9	55.49	75.58	-0.60	0.21s	1.58s	6.81	1
10	64.07	94.43	-0.07	0.20s	1.23s	7.32	1
11	74.90	61.09	-1.56	0.19s	2.49s	6.60	1
12	99.27	100.20	-0.08	0.147s	1.58s	7.34	1
13	131.87	14.69	-0.99	0.12s	14.7s	5.15	1

Based on Table 4.3, value for Kp, Ki and Kd at No.6 show the performance that meet the requirement in term of rise time (< 2s), settling time (< 2s), and overshoot (< 6.5%). At this performance, the tune value are Kp=31.87, Ki=69.78, and Kd=0.56. Even tough, at No.1 and No.13 show the smaller value for overshoot, but this both values show larger value of settling time compared to No.6. The smaller settling time is required in order to make the ballast tank system faster to stable at desired setpoint. However, the final value for all tunes is 1 after the controller is applied. This shows that the controller applied is very helpful to reduce steady state error of the system.

Therefore, the PID transfer function obtained from PID tuning method is shown in equation (4.3) below.

$$G_{pid} = 31.869 + \frac{69.78}{s} + 0.56188\,s \quad (4.3)$$

Where:

Kp = 31.87

Ki = 69.78

Kd = 0.56

4.5 Output Response for the Open Loop System and Close loop system (by Simulation)

Figure 4.6 and Figure 4.7 show the output response for open loop output response and close loop with PID controller output response respectively. These both systems are performed in the simulation by using Matlab software (refer to section 3.1.6 and section 3.2).

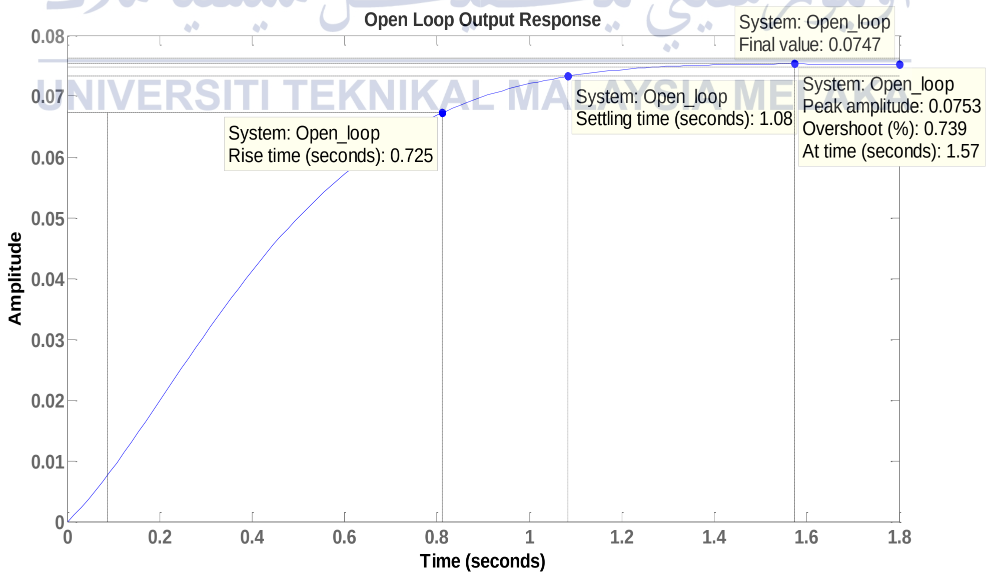


Figure 4.6: Open loop output response

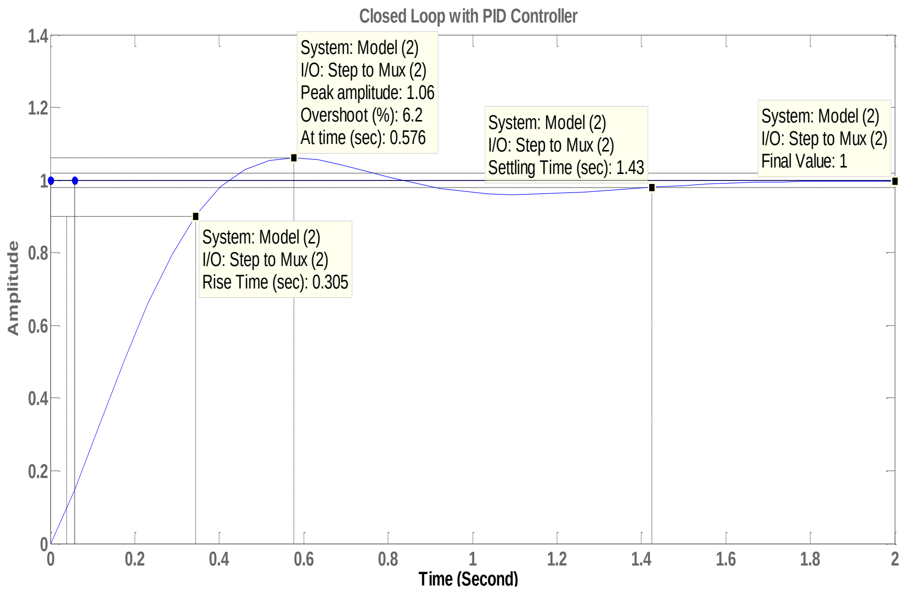


Figure 4.7: Close loop output response

Table 4.4 shows the comparison between the open loop system and closed loop (with PID controller) system. The input used is a step input, and both are compared in term of the performances of the output response.

Table 4.4: Comparison of the performance

Performance	**Open Loop**	**Closed Loop with PID Controller**
Rise Time, Tr	0.725s	0.305s
Settling Time, Ts	1.08s	1.43s
Percentage Of Overshoot, %OS	0.739	6.2
Final Value	0.0747	1
Steady State Error, e	0.9253	0

Based on Table 4.3, main problem for the open loop system is has a large steady state error. This shows that the actual depth level of the ballast tank has large deviation from the set point. But, this problem can be overcome by using close loop or feedback control system with an additional of controller. The purpose of using feedback control is to compensate for disturbances by measuring the output response, feeding that measurement back through a feedback path and comparing the response to the input at the summing junction [3].

In this project, the PID tuning method is used to design the suitable controller for the open loop system. All the values for Kp, Ki, and Kd obtained can be refer to section 3.2. After the PID controller is implemented, the rise time has improved to 0.305s, this make the system became more fast response toward the setpoint. This is because the proportional response can be adjusted by multiplying the error by a constant Kp, called the proportional gain constant[7]. However, the overshoot has increased to from 0.739 to 6.20. Consequently, this makes the output response to oscillate. Thus, the settling time also has increase to 1.43s. But, this still not large differ from the open loop output response that is only 0.35s deviation. The most important, the large steady-state error from open loop output response has improved to zero steady-state error.

4.6 The Result for Testing and Analysis Operation of Ballast Tank

This section will cover on two parts. Firstly, the performance of the ballast tank prototype. Secondly, the comparison between the system control level from surface with the system control level from bottom.

4.6.1 The Result for the Performance (Rise Time and Settling Time) of the Ballast Tank Prototype

Table 4.5 and Table 4.6 show the capability for open loop system and close loop system can maintain at certain level and rise back based on the different setpoint.

Table 4.5: Open loop system

Depth (cm)	Output Voltage (v)	Maintain Level	Rise
0	0.18	✓	✓
10	0.19	✓	✓
20	0.21	✓	✓
30	0.22	✓	✓
40	0.24	X	✓

Table 4.6: Closed loop system

Depth (cm)	Output Voltage (v)	Maintain Level	Rise
0	0.18	✓	✓
10	0.19	✓	✓
20	0.21	✓	✓
30	0.22	✓	✓
40	0.24	✓	✓
50	0.26	✓	✓
60	0.27	X	✓

Appendix K shows the entire graph for Experiment 4 that includes open loop system and close loop system. The experiment is repeated for three times at the same setpoint to prove the reliability of the data. Then, every one graph is selected from the Appendix K for each setpoint in order to obtain the performance of the ballast tank as shown in the Appendix L.

Next, Table 4.7 shows summarize all the performance for open loop system and close loop system (refer to Appendix L).

Table 4.7: Performance of the ballast tank

Set point	**Open-Loop System**	**Closed-Loop System (with PID controller)**
0.19 V (10 cm)	Tr = 94s Ts = 104s Final value = 10.24 Error = - 0.24	Tr = 81s Ts = 89s Final value = 10.29 Error = - 0.29
0.21 V (20 cm)	Tr = 178s Ts = 214s Final value = 23.15 Error = - 3.15	Tr = 148s Ts = 156 s Final value = 18.07 Error = 1.93
0.22 V (30 cm)	Tr = 197s Ts = 215s Final value = 28.35 Error = 1.65	Tr = 96s Ts = 151s Final value = 30.96 Error = - 0.96
0.24 V (40 cm)	-	Tr = 83s Ts = 116s Final value = 41 Error = - 1.00
0.26 V (50 cm)	-	Tr = 88s Ts = 116s Final value = 51 Error = - 1.00
0.27 V (60 cm)	-	-

By referring to Appendix M, the table 4.8 shows the performance of the closed loop system with applied of disturbance. Next, Table 4.9 shows the comparison in term of rise back between current ballast tank and previous ballast tank by past year final student.

Table 4.8: Closed-loop system (with PID controller) with applied of disturbance

Speed	300 rpm	200 rpm
Total weight of disturbance	120 g	80 g

Table 4.9: Comparison in term of rise back

Type	Rise back
Current ballast tank	Still can rise even at the bottom of underwater lab pool (110 cm)
Previous ballast tank	➢ 1st design = until 20 cm ➢ 2nd design = until 40 cm

During this experiment, the output voltage of the pressure sensor is not linear and consistent in underwater. Suppose the output voltage of pressure sensor should be proportional to depth level (refer to section 4.2). The main problem identified is because of the wire use for connecting pressure sensor to Arduino's microcontroller is not suitable for sending signal. Consequently, make the output voltage of pressure sensor is not consistent due to noise and delay.

Due to time constraint, the alternative solution suggested by supervisor for this problem is by replaced the pressure sensor to the variable resistor. The output voltage of the variable resistor is manually tuned during this experiment. The output voltage of variable resistor is tuned based on the characteristic of the pressure sensor with the depth level obtain from Experiment 2. This means, the variable resistor only will be tuned to certain voltage based on the depth position of ballast tank in underwater lab pool.

Basically, the output voltage from variable resistor plays an important role in the movement of the stepper motor either to pump water in, pump water out, or stop the motor. This output voltage will be send to the Arduino's microcontroller analog pin. Then, the Arduino's microcontroller will read the output voltage of the variable resistor and then compared to the input set.

For open loop system, the stepper motor will continue to pump water in if the output voltage less than the setpoint. Once, the output voltage is same or more than setpoint voltage, then the stepper motor will be stop rotation. Whereas, for close loop system the stepper motor will continue pump water in if the output voltage is less than the setpoint. The stepper motor will stop rotation when the output voltage is same with the setpoint. Lastly, the close loop system will pump water out if the output voltage is more than the setpoint.

The close loop system capable to maintain until 50cm depth compared to open loop system only 30cm depth (refer to Table 4.5 and Table 4.6). Moreover, the output response for close loop system shows an oscillation at setpoint 40cm and 50cm (refer Appendix L). But, the oscillation is only small variation. Thus, it can be state that the system still capable to maintain at this depth level. The oscillation occurs is because of the stepper motor pump water in and out when the output voltage is not same as input set. Next, at 60cm depth for closed-loop the ballast tank seem hard to maintain. So, this will be a limitation of this project. However, both open loop system and close loop system capable to rise back even already submerge until the lowest part in underwater lab pool which is at 110cm. By comparing with previous student, the ballast tank can only submerge and rise back at 20cm for first design, while 40cm for second design (refer to Table 4.9). Besides that, previous student also did not manage to implement PID controller in the real hardware. Thus, first objective of this project is success where the ballast tank designs capable to travel more deep and rise back.

Based on the Table 4.7, the closed loop system shows a better performance where the rise time and settling time is shorter than open-loop system. Rise time is time taken by a signal to change from a specified low value to a specified high value, mostly from 0.1 to 0.9 of its final value [7]. The shorter rise time shows the faster the system respond to reach its setpoint. While settling time is defined as the time for the response to reach, and stay within 2% of its final value [7]. For this project, it is necessary to have shorter settling time in order to make the ballast tank quickly stable and maintain at certain level. Besides that, closed loop system also shows a better performance in term of steady-state error compared from open-loop system. Steady-state error is defined as the difference between output of the system with the setpoint in the limit as time goes to infinity [7].

Therefore, the second objective of this project is achieved where by designing the suitable PID controller can improve the performance of open loop system. There are three separate constant parameters in the PID controller algorithm which is the proportional, the integral and derivative values. The proportional term produced an output value that is proportional to the current error value [7]. This means when the current error of the ballast tank position is large, than the output value produced also large to make the system toward the setpoint. Next, the integral term accelerate the movement of the process toward setpoint and eliminate the residual steady-state error [7]. Thus, the integral value make the ballast tank accelerate the movement of process where the shorter rise time is produced, and the steady-state error also has improved. Lastly, the derivative value predicts system behavior and thus improved the settling time and stability of the system [7]. The implement of the derivative helps the ballast tank to improve the settling time and stable with faster.

Basically, when the disturbance is applied the ballast tank will move downward because the weight is added. Based on the experiment was conducted (refer Appendix M), 300rpm shows the better performance in maintaining depth and also in overcome the disturbance. Even tough, at speed 300rpm has more overshoot. The amount of disturbance is more large can be applied to system at 300rpm which is 120g compared to system at 200rpm only can handle until 80g. After this amount of disturbance is applied to the top of ballast tank (300rpm and 200rpm), the ballast tank seems hard to maintain at 20cm depth anymore. However, the ballast tank still can rise back even amount of this screw is added. So, the limitation is set based on the ballast tank cannot maintain at 20cm. Therefore, the bigger rpm used give more disturbances can be applied to the ballast tank and also make the ballant tank faster reach the setpoint.

4.5.2 Compare the Algorithm between the System Control Level from surface with the System Control Level from bottom

Table 4.10 shows the comparison between the systems control level from surface with the system control level from bottom. Appendix N shows the entire graph for the system control level from bottom.

Table 4.10 Comparison of the algorithm

Characteristic	System control level from surface	System control level from bottom
Type of sensor	Pressure sensor	Ultrasonic sensor
Open-loop system	➢ Setpoint = 10 cm Tr = 94s, Ts = 104s ➢ Setpoint = 20 cm Tr = 190s, Ts = 210s ➢ Setpoint = 30 cm Tr = 173s, Ts = 215s	➢ Setpoint = 94 cm Tr = 27s, Ts = 29s ➢ Setpoint = 84 cm Tr = 16s, Ts = 71s ➢ Setpoint = 74 cm Tr = 32s, Ts = 78s
Closed-loop system (with PID controller)	➢ Setpoint = 10 cm Tr = 80s, Ts = 88s ➢ Setpoint = 20 cm Tr = 147s, Ts = 155s ➢ Setpoint = 30 cm Tr = 96s, Ts = 151s ➢ Setpoint = 40 cm Tr = 82s, Ts = 119s ➢ Setpoint = 50 cm Tr = 73s, Ts = 146s	➢ Setpoint = 94 cm Tr = 239s, Ts = 269s ➢ Setpoint = 84 cm Tr = 26s, Ts = 224s ➢ Setpoint = 74 cm Tr = 120s, Ts = 195s ➢ Setpoint = 64 cm Tr = 35s, Ts = 55s ➢ Setpoint = 54 cm Tr = 13s, Ts = 40s
Limitation	➢ Open-loop system - Until 30cm depth ➢ Closed-loop system	➢ Open-loop system - Until 30cm depth ➢ Closed-loop system

	(with PID controller) - Until 50cm depth	(with PID controller) - Until 50cm depth
Disturbance	➢ 300 rpm - 120g ➢ 200 rpm - 80g	➢ 300 rpm - 160g ➢ 200 rpm - 120g

Based on Table 4.10, both systems are used the different type of sensor which are pressure sensor for surface system and ultrasonic sensor for bottom system. Depth level is same between the setpoint for system control level from surface and system control level from bottom. The different only pressure sensor read signal from desired depth level to surface, while the ultrasonic read from the desired depth level to bottom. Figure 4.8 shows the illustration for this situation.

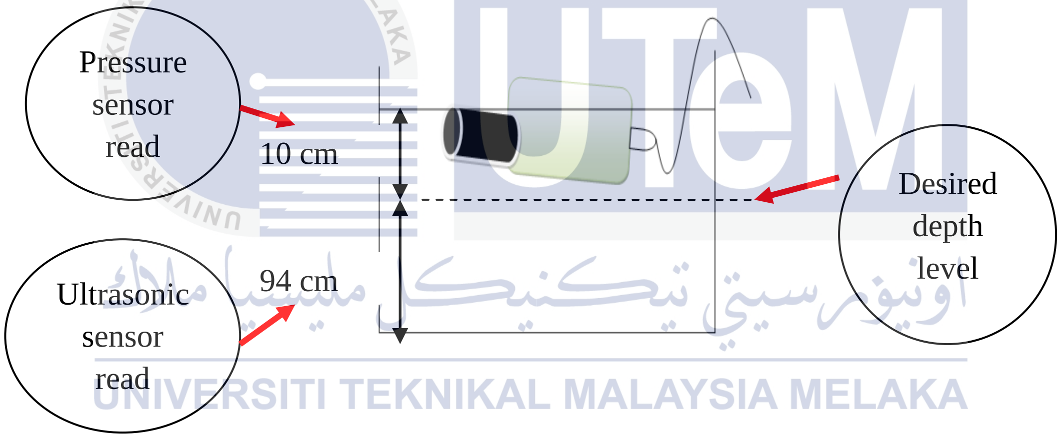


Figure 4.8: Illustration setpoint for both systems at same depth level

Even tough, both systems implement same values for Kp, Ki, and Kd in the algorithm system. The system control level from surface shows the improvement of rise time and settling time when the closed-loop system (with PID controller) is implemented. However, the system control level from bottom shows the improvement of the rise time and settling time only at setpoint 64cm and 74cm. Figure 4.9 and Figure 4.10 show the illustration for output respond of both algorithms system based on position error.

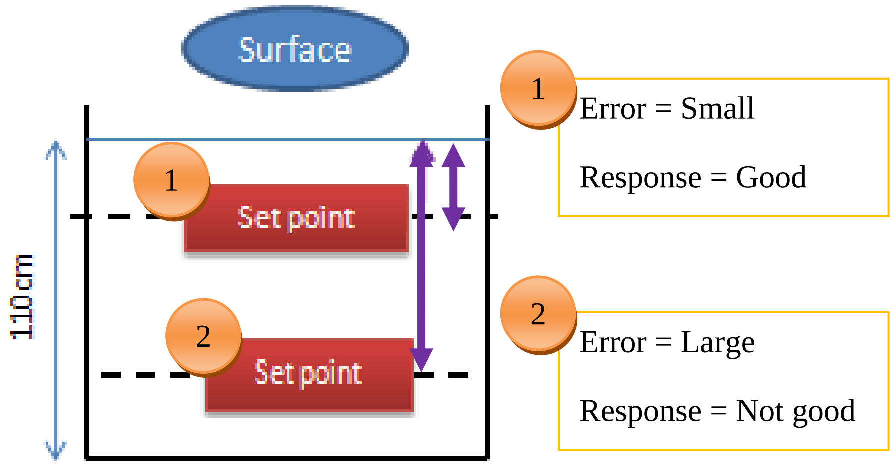


Figure 4.9: System from surface

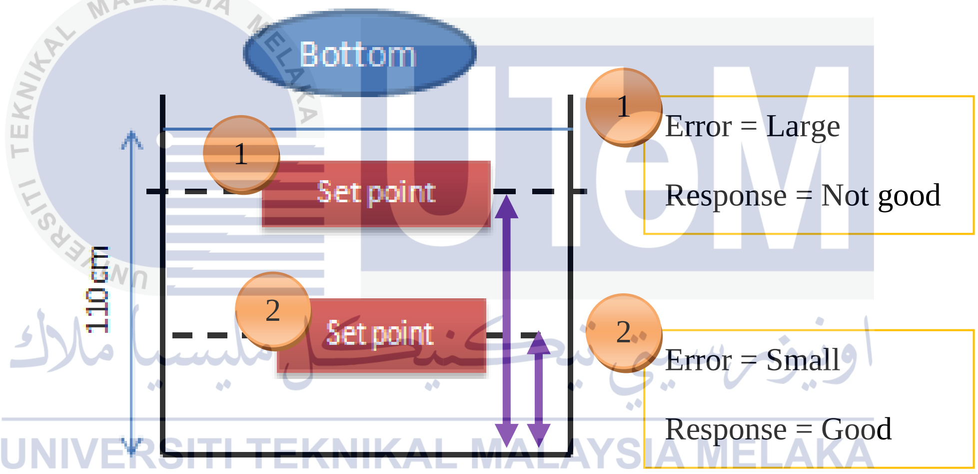


Figure 4.10: System from bottom

Therefore, future ballast tank can used both algorithm system (by switching) to control depth level based on suitable depth. Figure 4.11 shows the illustration of the switching algorithm based on suitable depth error.

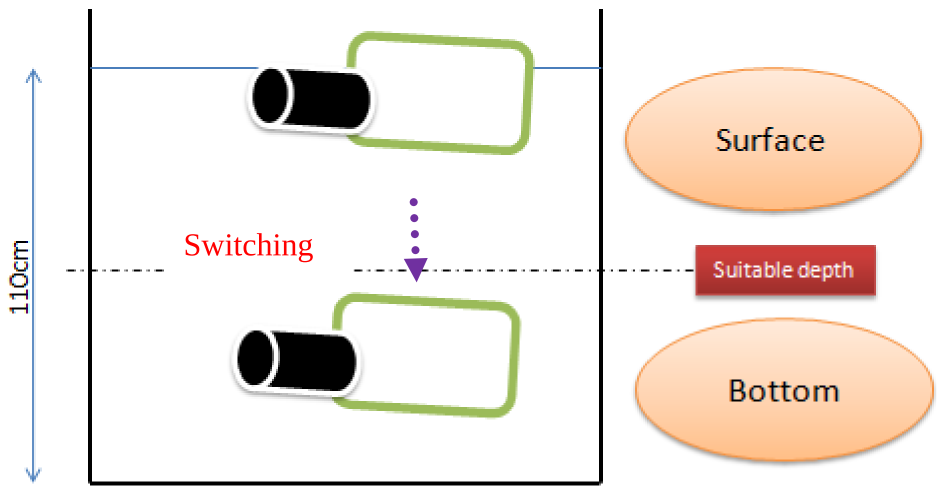


Figure 4.11: Combination of algorithm in ballast tank system

Besides that, both systems show the same limitation on maintaining at certain depth which is until 30cm for open-loop system and 50cm for closed-loop system. This is due to the hardware used is same for both of systems. Both systems show a better performance at 300rpm speed of stepper motor. This is because the bigger of rpm selected will make the system to move faster and also fast react to overcome the disturbance applied. However, system control level from bottom shows more disturbances can be applied which are 160 g at 300 rpm, and 120 g at 200 rpm. The is because system control level used variable resistor to replaced pressure sensor, then the output voltage is a little bit difficult to vary correspond to effect of disturbance applied. However, this problem more easy to be encountered in open loop system and close system, since the ballast tank movement is more linearly compared to disturbance applied (drastically change).

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.0 Introduction

This chapter will conclude all the result from the experiment that has been conducted. Besides that, this chapter also will state the main factors that happen when completing this project. Lastly, this chapter also will recommend some suggestion such as a new design or additional procedure that need to be considered. Thus, this recommendation will help others people to do more research.

5.1 Conclusion

The first objective of this project is to develop a ballast tank. In particular, the objective has been successfully accomplished due to the ballast tank able to maintain at certain depth based on the setpoint set. Besides that, this project also improved the previous ballast tank design by past year student. This report has described in detail about the development of the ballast tank system at section 3.1. The pressure sensor from MPX420GP model was used in this project as a control feedback. However, due to noise and delay on the reading signal from sensor, the sensor was replaced with the variable resistor. But, the variable resistor will be manually tuned based on the output voltage obtain from the characteristic of pressure sensor with depth level (refer to section 3.1.4).

Firstly, the air pump is selected because it has bigger diameter and volume compared to previous ballast tank design by previous final year student (refer Table 3.2). When the ballast tank is bigger it will capable to pump water in much more quantity and thus will help the ballast tank to submerge in more depth level and rise back. In this project, the piston ballast tank is selected because it has accurate buoyancy control compared to pump system. Next, the stepper motor is used in this experiment because it has a high torque compared to DC motor. Since, the underwater is dealing with high pressure, so the stepper motor is more practical to be used because it has a high torque where can handle a high pressure.

The second objective of this project is to design proportional integral and derivatives (PID) controller system in order to improve the performance of the ballast tank system. The PID controller is obtained by using the PID tuning method. Then, this PID controller is implemented to the real hardware to observe the improvement of the performance. Based on the experiment conducted, the ballast tank for close loop system can maintain up to 50cm compared to open-loop system only 30cm. Besides that, PID controller helps the system to increase the response in term of rise time and settling time. Lastly, the steady state error also reduced when using PID controller. Thus, second objective of this project also success.

The system also has the feedback from the MPX420GP pressure depth sensor that function to detect pressure and convert it into voltage level. Then, the feedback voltage has been compared with the input set in the Arduino's microcontroller in order to control the movement of the piston ballast tank. But, as mentioned before this pressure sensor was replaced with the variable resistor due to some noise and delay that cause the system not function well.

The third objective is to compare the algorithm system of the ballast tank between the systems control level from surface and the system control level from bottom. Based on the comparison, both systems show the improvement when the PID controller is applied. Both systems show the same limitation where open-loop system at 30cm depth, while for closed-loop with PID controller is at 50cm. However, in terms of rise time and settling time both systems show dissimilarities. Future ballast tank can used both algorithms system (by switching) to control depth level based on suitable depth error. The reason already discovered in the result and analysis part. In a nut shell, both systems also show a same characteristic for the experiment with applied of disturbance. The system at 300 rpm shows the best performance compared to 200 rpm. In addition, the system at 300 rpm makes the ballast tank handle more disturbances applied.

5.2 Recommendation

In order to improve this project, there are 5 recommendations that have been recognizing through this project. First, the intelligent controller such as fuzzy logic can be implemented to observe the performance of the ballast tank system compared to the conventional controller.

Second is selecting the suitable o-ring for piston and need to be really fixed with the ballast tank. The reason is to avoid leakage into ballast tank and can destroy the stepper motor. Besides that, to prevent the leakage also can be done by using a proper sealing technique that is suitable patch from underwater specification.

Third recommendation is regarding on the body of the ballast tank. Instead of using the Tupperware, it us much more suitable and proper to fabricate a fiber glass or use aluminum material as the body if there is an extra budget. Since, the Tupperware can release the air inside the body through the cover when it is compressed at high pressure.

The fourth is regarding on the cable used for reading signal from the pressure sensor. In this project, the electrical wire is used to read the signal from the sensor toward the Arduino’s analog pin. However, this wire produces noise and delay when it is attached to ballast tank. Therefore, the signal cable for underwater application is recommended in order to obtain the consistent signal from the pressure sensor.

The fifth is a supply cable used for stepper motor also must from the underwater cable which is neutral buoyancy. This is because the current cable gives the effect (additional weight) on the buoyancy of the ballast tank.

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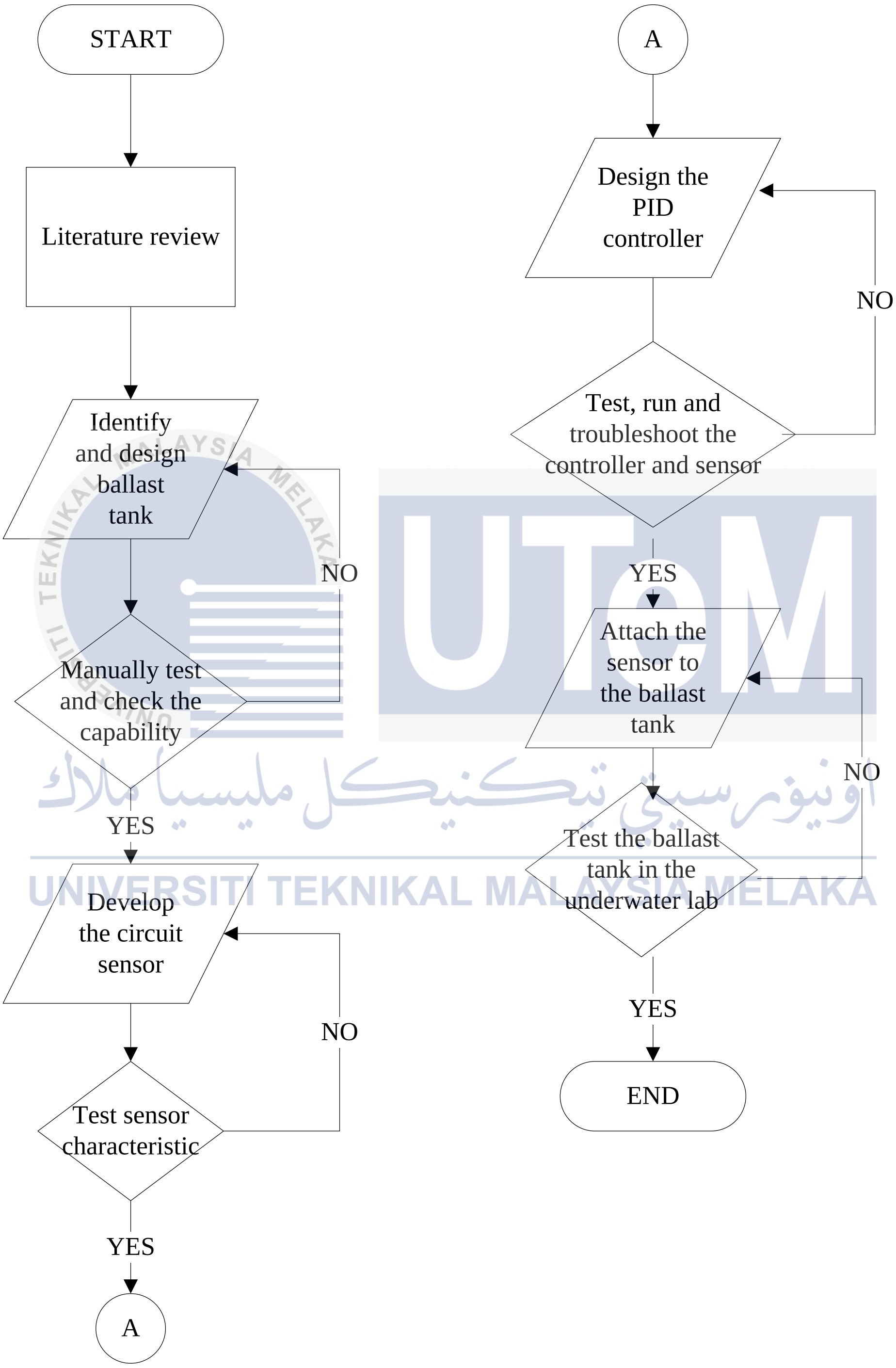
APPENDIX A

1) PSM flowchart

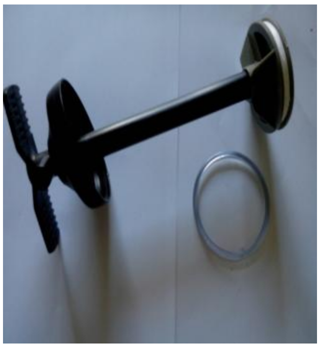


APPENDIX B

2) List Parts of the Piston Ballast Tank

- Air pump

In this project air pump is used as the whole ballast tank system.



- Pipe tape

This pipe tape is placed at moveable piston before put the o ring. The purpose is to avoid from water leakage.

- Rod with thread

This rod with thread will be joined with air pump component as moveable piston in the ballast tank system.

- Bevel gear

The main purpose of using bevel gear is to change the rotation of stepper motor for 90 degree. One of another bevel gear will has thread inside in order to move movable piston.

- Bearing

The function of bearing is to provide free linear movement of the moving part or for free rotation around a fixed axis [3]. In this project, the position of bevel gear is hold by bearing. Besides that, bearing also provide free rotation of bevel gear.

- Tupperware

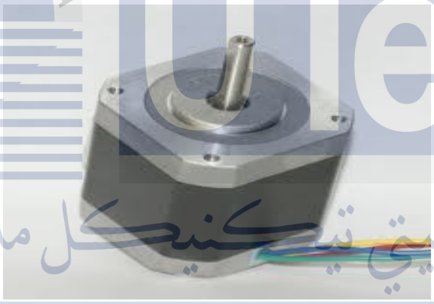
The Tupperware is used as the container for all electrical components such as stepper motor and driver. This type of Tupperware is chosen because highly seal that can prevent from the water go inside and damage the components.

➢ Silicon sealant

The purpose of using silicon is want to seal the container from the water goes in. This silicon is applied when there is another component joining to the container.

➢ Stepper Motor CRK PK566NAW

Stepper motor is very important in this project where this stepper motor will be used to move the piston in ballast tank either to suck water in or out.



APPENDIX C

3) Assemble Process for Mechanical Ballast Tank.

Process 1

The assemble part start with the process of replace actual pump piston with the rod with thread .

↓

Process 2

Rod thread piston is attach to bevel gear with the thread inside.

↓

Process 3

Bevel gear is hold by the bearing. Mounting the bearing at fixed position.

↓

Process 4

Another bevel gear is attacth to the stepper motor. Stepper motor is mount at fixed position where the piston of bevel gears are perpandicular to each other.

↓

Process 5

Complete the mechanical part ballast tank process.

↓

Process 6

Attach mechanical part ballast tank to the tupperware.

↓

Process 7

Completely seal the tupperware with silicon sealant.

APPENDIX D

4) Weight Estimation Calculation

i) Main Body

$\sum Fv = 0$

Fb = Fe + W

m = 3.0 kg

$Fb = \gamma f \times Vd$

$V = L \times W \times H$

= 24cm × 16.5 cm × 14.5cm

= 5742 cm^3

= 5742×10^3 mm^3

Where, $\gamma f = 9.81 \times 10^3\ N/m^3$

$$Fb1 = \left(\frac{9.81\times10^3}{m^3}\right)(5742\ \times 10^3 mm^3)\left(\frac{1m^3}{10^3 mm^3}\right)$$

= 56.32 N

$Fe1 = Fb1 - W1$

$= 56.32 - (3.0\ \times 9.81)$

= 26.89 N

ii) <u>Ballast tank</u>

m = 0.3 kg

$V = \pi r^2 \times L$

$= \left(3.142 \times \left(\frac{7.3cm}{2}\right)^2\right) \times 15.3cm$

$= 640.45\ cm^3$

$= 640.45 \times 10^3 mm^3$

Fb2= $\left(\frac{9.81 \times 10^3}{m^3}\right)(640.45 \times 10^3 mm^3)\left(\frac{1m^3}{10^3 mm^3}\right)$

= 6.28N

Fe2=Fb2 – W2

= 6.28 – (0.3 × 9.81)

= 3.34 N

iii) <u>For the total weight</u>

W = W1 + W2

= 26.89 N + 3.34 N

= 30.23 N

iv) <u>Convert Newton to kg</u>

W = mg

M = $\frac{w}{g}$ = $\frac{30.23}{9.81}$ = 3.08 kg

APPENDIX E

5) Coding for Manually Control Depth Level

```
#include <Stepper.h>
#define motorSteps 200     // change this depending on the number of steps
                           // per revolution of your motor
#define motorPin1 8
#define motorPin2 10


// initialize of the Stepper library:
Stepper myStepper(motorSteps, motorPin1,motorPin2);


void setup() {
  // set the motor speed at 300 RPMS:
  mySteppe r.setSpeed(300);
  // Initialize the Serial port:
  Serial.begin(9600);
}


void loop() {
  // Step backward 34000 steps:
  Serial.println("Backward");
  myStepper.step(-34000);
  delay(100);



  // Step forward 34000 steps:
```

```
  Serial.println("Forward");
  myStepper.step(34000);
  delay(100);
}
```

APPENDIX F

6) Manual Control Depth Level

TIME(S)	PISTON MOVE (MM)	DEPTH(mm)
0	0	0
1	0.73	0
2	1.46	0
3	2.19	0
4	2.92	0
5	3.65	0.5
6	4.38	0.5
7	5.11	0.5
8	5.84	1
9	6.57	1
10	7.3	1.5
11	8.03	1.5
12	8.76	2
13	9.49	2
14	10.22	2.5
15	10.95	2.5
16	11.68	3
17	12.41	3
18	13.14	3
19	13.87	3.5
20	14.6	3.5
21	15.33	4
22	16.06	4
23	16.79	4.5
24	17.52	5
25	18.25	5.5
26	18.98	6
27	19.71	7
28	20.44	7.5
29	21.17	8
30	21.9	9
31	22.63	10
32	23.36	11
33	24.09	12
34	24.82	13
35	25.55	14
36	26.28	15
37	27.01	16
38	27.74	17
39	28.47	18
40	29.2	19
41	29.93	20
42	30.66	21
43	31.39	22
44	32.12	24
45	32.85	26
46	33.58	27
47	34.31	29
48	35.04	30
49	35.77	31
50	36.5	32
51	37.23	33
52	37.96	35
53	38.69	37
54	39.42	38
55	40.15	39
56	40.88	40
57	41.61	41
58	42.34	42.5
59	43.07	43.5
60	43.8	45
61	44.53	47
62	45.26	48
63	45.99	49.5
64	46.72	51
65	47.45	52.5
66	48.18	54
67	48.91	56
68	49.64	58
69	50.37	59.5
70	51.1	63
71	51.83	64

72	52.56	66
73	53.29	67
74	54.02	70
75	54.75	71
76	55.48	75
77	56.21	76.5
78	56.94	78
79	57.67	81
80	58.4	84
81	59.13	86
82	59.86	89
83	60.59	92
84	61.32	94
85	62.05	97
86	62.78	99
87	63.51	103
88	64.24	105
89	64.97	108.5
90	65.7	111
91	66.43	114
92	67.16	118
93	67.89	122
94	68.62	126
95	69.35	131
96	70.08	135
97	70.81	139
98	71.54	145
99	72.27	148.5
100	73	164
101	73.73	170
102	74.46	178
103	75.19	184.5
104	75.92	190
105	76.65	197
106	77.38	203
107	77.38	207
108	77.38	211
109	77.38	214
110	77.38	216
111	77.38	217
112	76.65	220
113	75.92	221
114	75.19	220

115	74.46	220
116	73.73	220
117	73	218.5
118	72.27	218.5
119	71.54	217
120	70.81	217
121	70.08	215.5
122	69.35	214.5
123	68.62	213.5
124	67.89	211
125	67.16	210
126	66.43	208
127	65.7	203
128	64.97	201
129	64.24	199
130	63.51	196
131	62.78	193
132	62.05	192
133	61.32	191
134	60.59	188
135	59.86	186
136	59.13	183
137	58.4	179
138	57.67	174
139	56.94	171
140	56.21	168
141	55.48	163.5
142	54.75	160
143	54.02	157
144	53.29	154
145	52.56	149
146	51.83	143
147	51.1	137
148	50.37	134
149	49.64	131
150	48.91	129
151	48.18	126
152	47.45	117
153	46.72	114
154	45.99	110
155	45.26	106
156	44.53	102
157	43.8	99

158	43.07	96
159	42.34	91
160	41.61	88
161	40.88	85
162	40.15	81
163	39.42	80
164	38.69	73
165	37.96	70
166	37.23	65
167	36.5	63
168	35.77	61
169	35.04	56
170	34.31	53
171	33.58	51
172	32.85	50
173	32.12	47
174	31.39	46
175	30.66	43
176	29.93	42
177	29.2	42
178	28.47	42
179	27.74	38
180	27.01	37
181	26.28	36
182	25.55	36
183	24.82	34
184	24.09	33
185	23.36	31
186	22.63	29
187	21.9	28
188	21.17	27
189	20.44	25
190	19.71	24
191	18.98	21
192	18.25	20.5
193	17.52	19.5
194	16.79	19
195	16.06	17
196	15.33	15
197	14.6	14
198	13.87	13
199	13.14	13
200	12.41	12

201	11.68	10
202	10.95	9.5
203	10.22	9
204	9.49	7
205	8.76	5
206	8.03	4
207	7.3	3
208	6.57	2
209	5.84	1
210	5.11	0
211	4.38	-2
212	3.65	-2
213	2.92	-2.5
214	2.19	-3
215	1.46	-3
216	0.73	-4
217	0	-4.5
218	0	-5
219	0	-5
220	0	-5
221	0	-5
222	0	-5
223	0.73	-5
224	1.46	-5
225	2.19	-4.5
226	2.92	-4.5
227	3.65	-4.5
228	4.38	-4.5
229	5.11	-4
230	5.84	-4
231	6.57	-4
232	7.3	-3.5
233	8.03	-3
234	8.76	-2
235	9.49	1
236	10.22	2.5
237	10.95	3
238	11.68	4.5
239	12.41	6
240	13.14	7.5
241	13.87	8.5
242	14.6	10
243	15.33	12.5

244	16.06	13.5
245	16.79	15
246	17.52	16.5
247	18.25	17.5
248	18.98	19
249	19.71	21.5
250	20.44	22
251	21.17	23.5
252	21.9	26
253	22.63	27
254	23.36	29
255	24.09	31
256	24.82	33
257	25.55	35
258	26.28	36
259	27.01	38
260	27.74	40
261	28.47	43
262	29.2	46
263	29.93	49
264	30.66	50
265	31.39	52
266	32.12	54
267	32.85	56
268	33.58	57.5
269	34.31	59.5
270	35.04	61
271	35.77	63
272	36.5	64
273	37.23	65
274	37.96	66
275	38.69	66.5
276	39.42	66.5
277	40.15	67
278	40.88	67.5
279	41.61	68.5
280	42.34	69.5
281	43.07	70
282	43.8	71
283	44.53	72
284	45.26	72.5
285	45.99	74
286	46.72	75

287	47.45	77
288	48.18	78.5
289	48.91	79.5
290	49.64	81
291	50.37	83
292	51.1	84
293	51.83	85.5
294	52.56	87
295	53.29	89
296	54.02	90.5
297	54.75	92
298	55.48	94
299	56.21	97
300	56.94	99.5
301	57.67	101
302	58.4	103.5
303	59.13	105
304	59.86	107.5
305	60.59	110
306	61.32	113.5
307	62.05	117
308	62.78	120
309	63.51	123.5
310	64.24	127
311	64.97	130
312	65.7	134.5
313	66.43	139
314	67.16	144
315	67.89	148
316	68.62	151
317	69.35	155
318	70.08	159
319	70.81	163
320	71.54	168
321	72.27	173
322	73	178
323	73.73	183
324	74.46	190
325	75.19	194
326	75.92	199
327	76.65	210
328	77.38	217
329	77.38	225

330	77.38	228
331	77.38	230
332	77.38	231
333	77.38	231
334	76.65	231
335	75.92	230
336	75.19	230
337	74.46	229
338	73.73	223
339	73	222
340	72.27	219
341	71.54	217
342	70.81	214.5
343	70.08	212
344	69.35	211
345	68.62	207
346	67.89	205
347	67.16	202
348	66.43	200.5
349	65.7	199
350	64.97	197
351	64.24	193
352	63.51	190
353	62.78	186.5
354	62.05	185.5
355	61.32	183
356	60.59	181.5
357	59.86	180
358	59.13	175
359	58.4	171
360	57.67	169.5
361	56.94	166
362	56.21	164
363	55.48	160
364	54.75	159
365	54.02	156.5
366	53.29	155
367	52.56	152
368	51.83	148
369	51.1	142
370	50.37	137.5
371	49.64	130.5
372	48.91	125

373	48.18	119.5
374	47.45	115
375	46.72	112
376	45.99	109
377	45.26	105.5
378	44.53	102
379	43.8	98
380	43.07	96
381	42.34	92
382	41.61	90
383	40.88	86
384	40.15	84
385	39.42	81
386	38.69	79
387	37.96	78
388	37.23	73
389	36.5	72
390	35.77	68
391	35.04	65
392	34.31	64
393	33.58	63
394	32.85	59.5
395	32.12	57.5
396	31.39	55.5
397	30.66	54.5
398	29.93	52
399	29.2	50.5
400	28.47	49.5
401	27.74	48
402	27.01	46.5
403	26.28	44
404	25.55	43
405	24.82	41
406	24.09	39
407	23.36	38
408	22.63	37.5
409	21.9	36
410	21.17	34
411	20.44	33
412	19.71	32.5
413	18.98	32
414	18.25	31
415	17.52	30

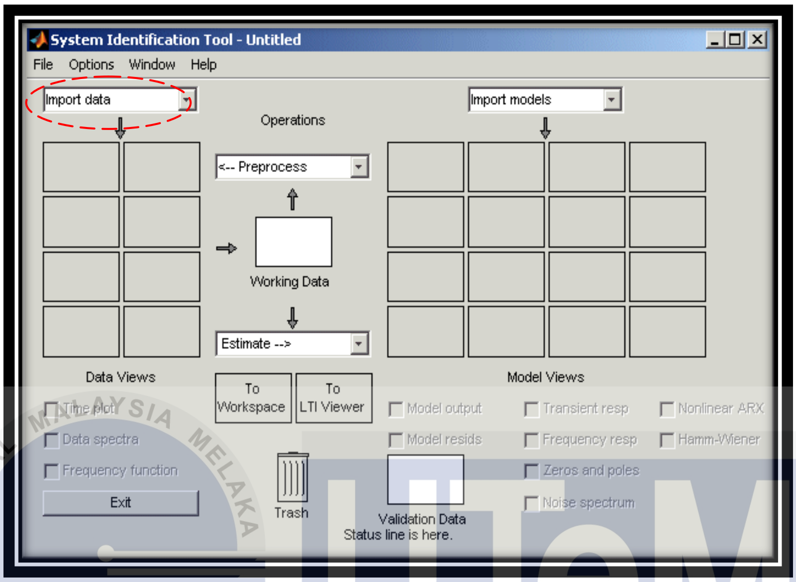
416	16.79	28.5
417	16.06	27.5
418	15.33	26
419	14.6	25
420	13.87	23.5
421	13.14	22
422	12.41	21
423	11.68	18
424	10.95	15.5
425	10.22	13
426	9.49	12
427	8.76	10.5
428	8.03	8
429	7.3	6
430	6.57	4

431	5.84	3
432	5.11	2
433	4.38	1
434	3.65	0
435	2.92	0
436	2.19	-0.5
437	1.46	-1
438	0.73	-2
439	0	-3
440	0	-4
441	0	-4
442	0	-4
443	0	-4
444	0	-4.5

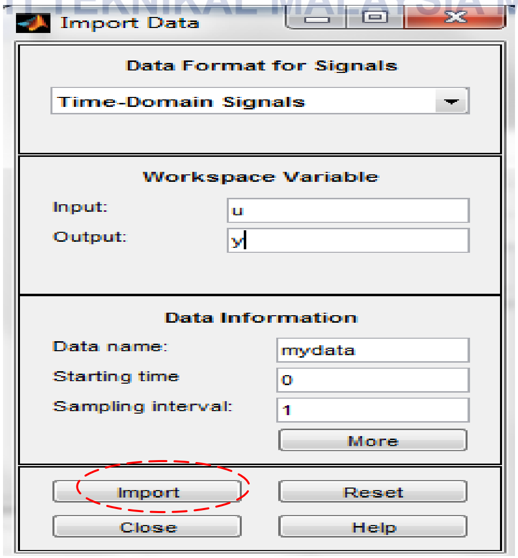
APPENDIX G

7) System Identification

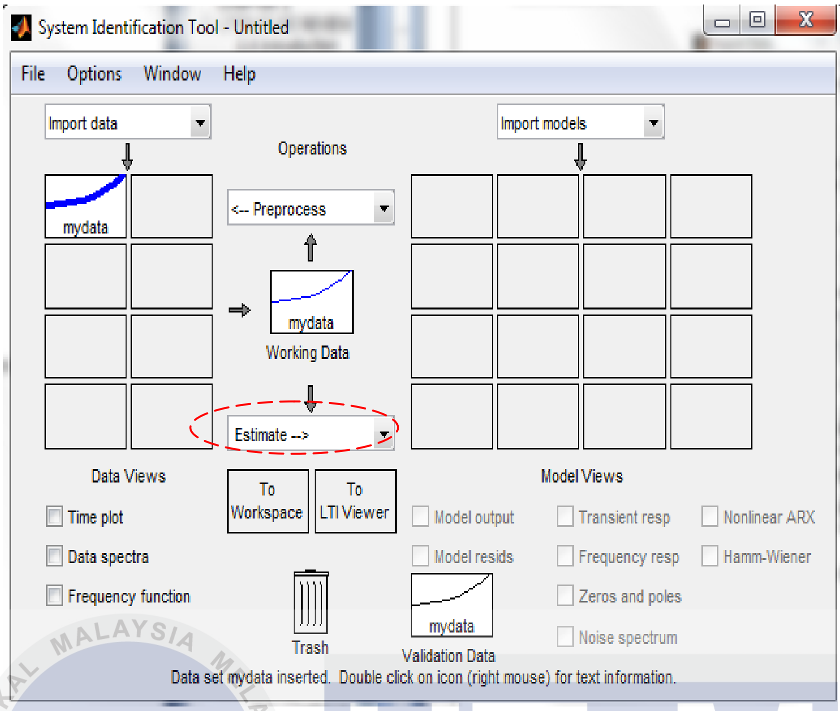
- STEP1: Type command "ident" at the command window to generate System Identification Toolbox



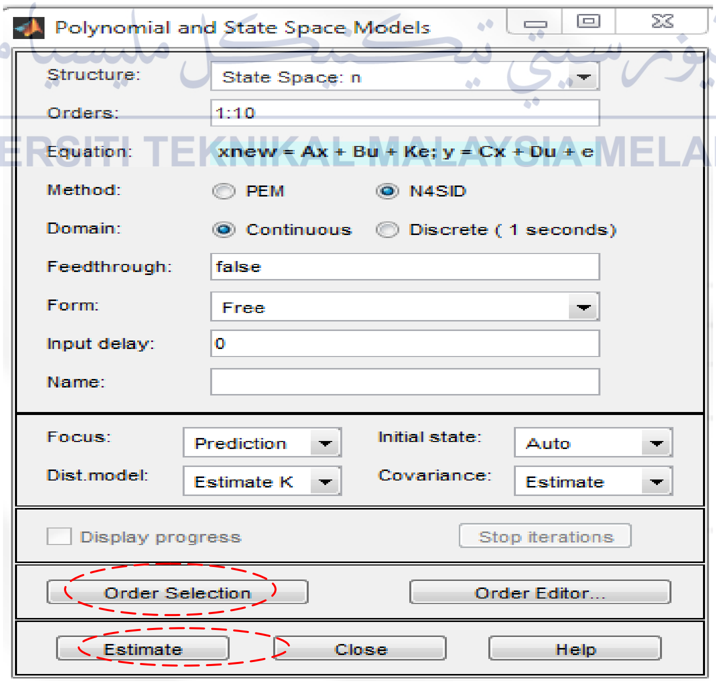
- STEP 2: The "Time Domain Data" were selected from the "import data" at the System Identification Tool. The import data GUI where u (the piston movement) is set as an input and y (depth level) is set as output. The "Import" button is clicked to import data to the system identification tool.



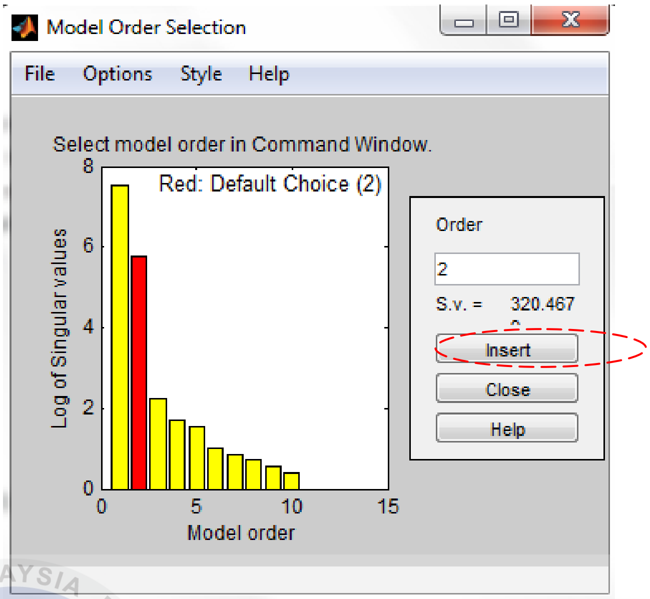
- STEP 3: The “polynomial model” is selected in drop down estimate list



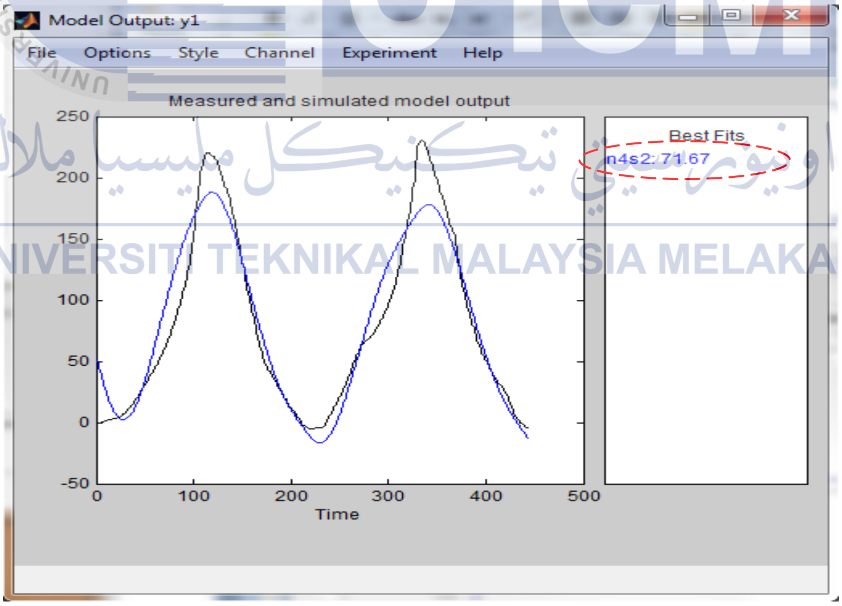
- STEP 4: In the polynomial and state space model the “state space” is selected at the structure down list. Then, the “Order Selection” is clicked followed by “Estimation” button to perform estimation



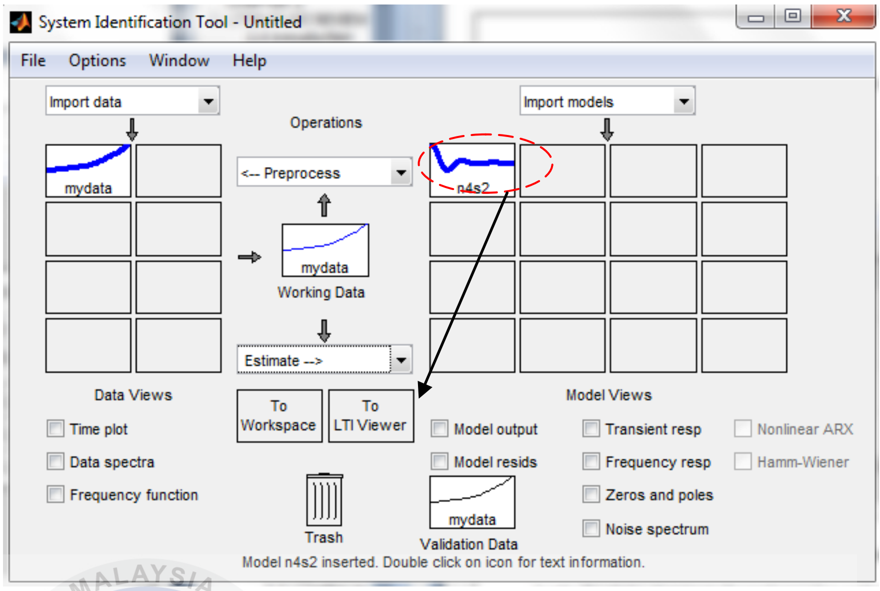
➢ STEP 5: The "insert" button is clicked in the Model Oder Selection in order to add the estimated model into the main GUI



➢ STEP 6: The best fit for this transfer function (n4s2) is equal to 71.67 which are almost to 80 (theoretical)



➢ STEP 7: Lastly, the n4s4 is dragging to the workspace box under the main GUI. This will make the model is exported to the MATLAB Workspace.



➢ STEP 8: Then, the command below is typing at the command window in order to extract the matrices, and convert from state space to the transfer function.

A=n4s2.A;

B=n4s2.B;

C=n4s2.C;

D=n4s2.D;

Extract the matrices

Gz_ss=ss(A,B,C,D,1); → In discrete

Gs_ss=d2c(Gz_ss); → In continues

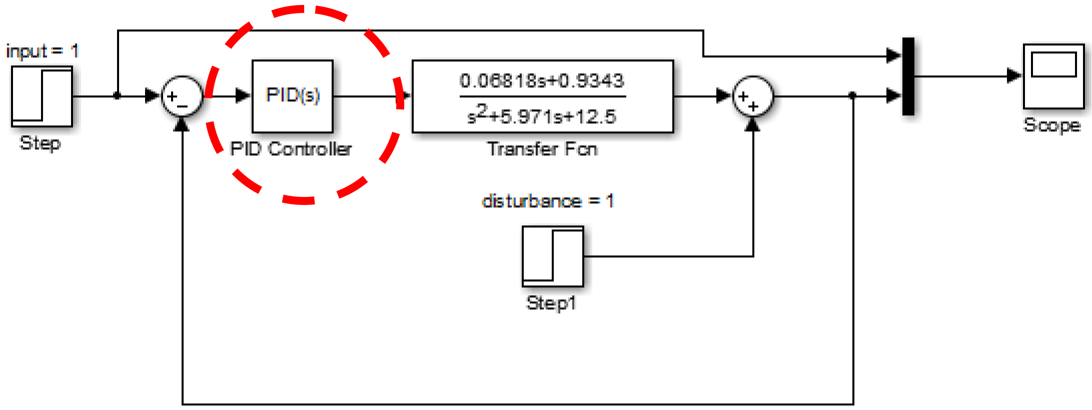
Gs_tf=tf(Gs_ss); → Transfer Function

step(Gs_tf);

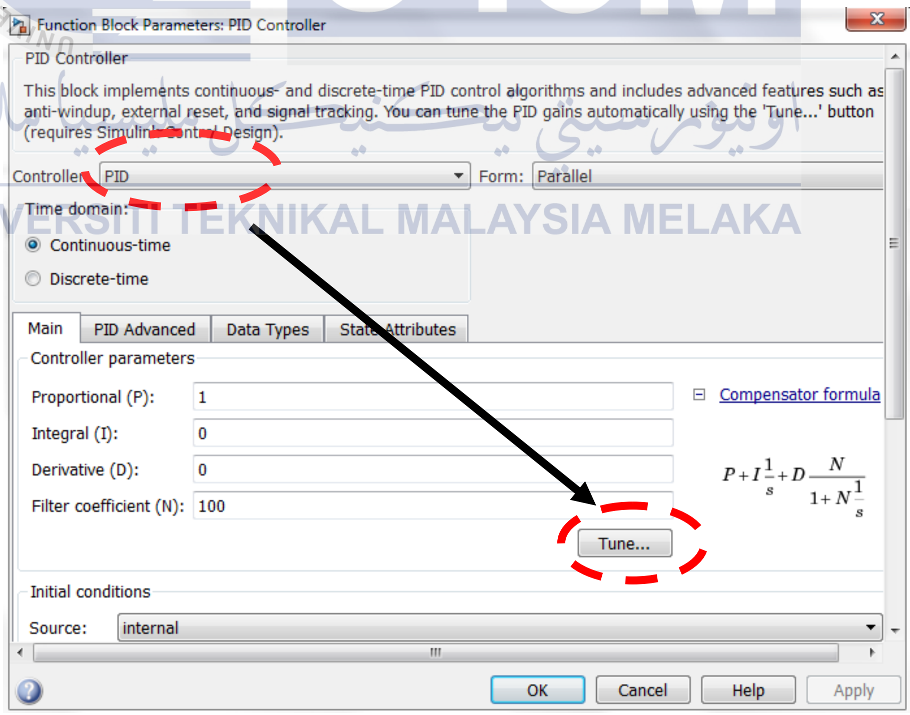
APPENDIX H

8) PID Tuning Method (Manually Tune)

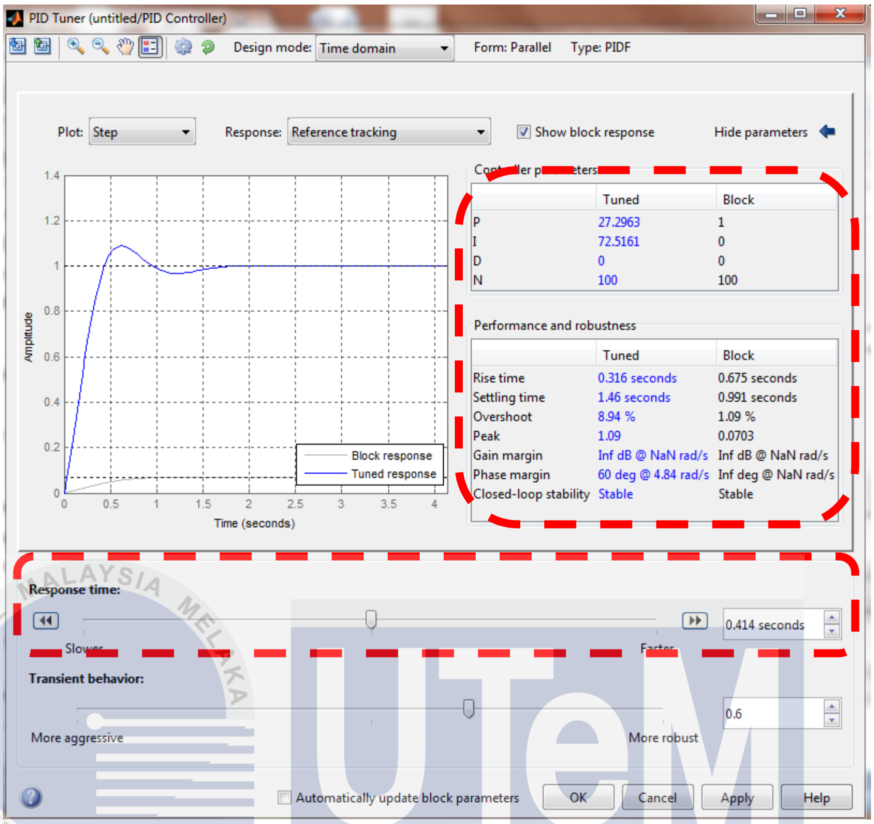
- STEP 1: Double click the "PID Controller" block diagram



- STEP 2: The "PID" is selected in drop down Controller list. Then, "Tune" button is pressed



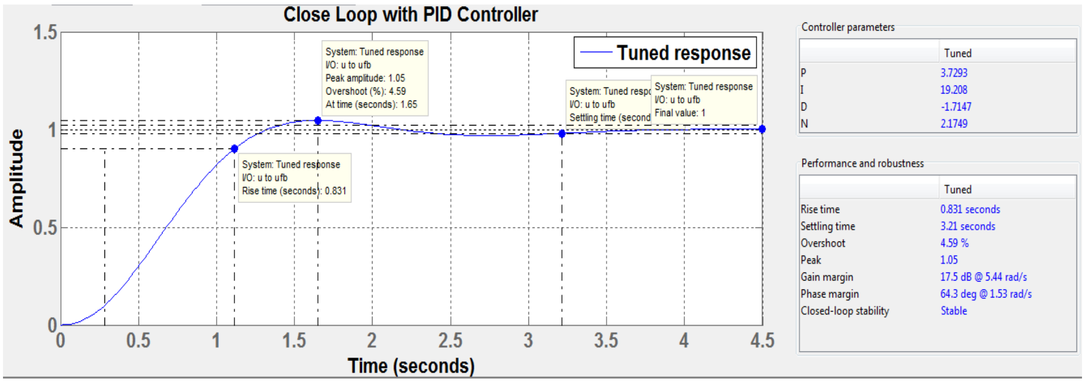
- STEP 3: Obtain the performance of the response by adjusting the "Response time"



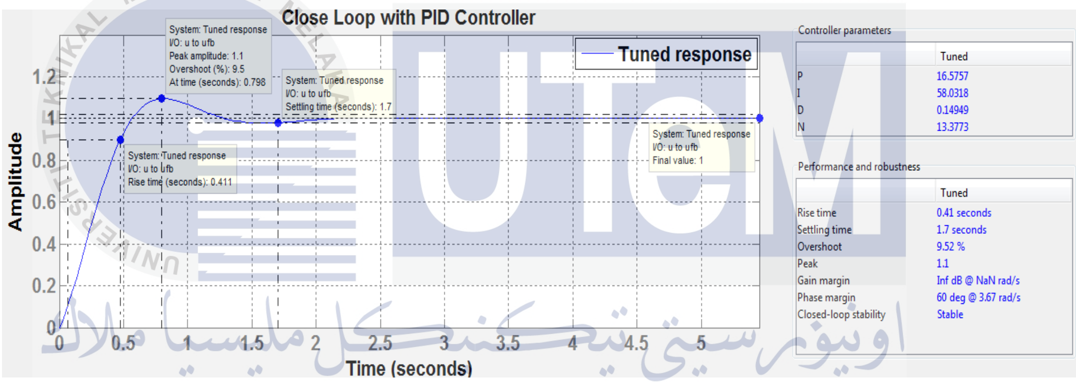
APPENDIX I

9) System Performance at Different Values of Kp, Ki, and Kd

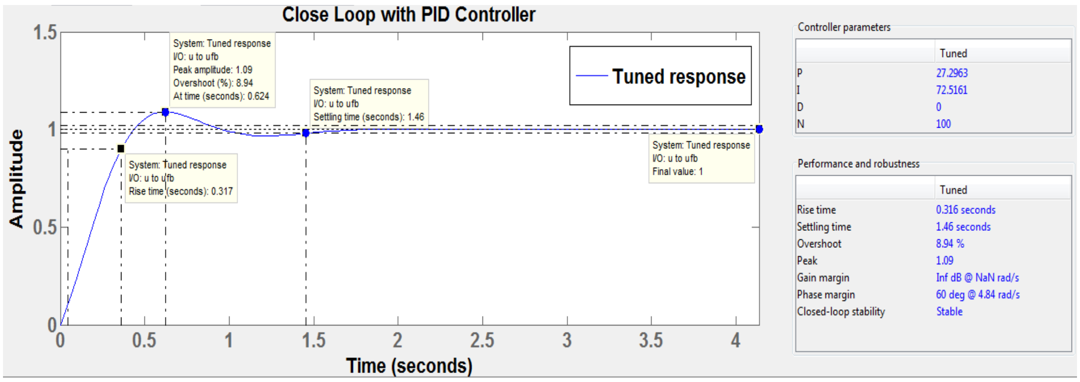
- No.1



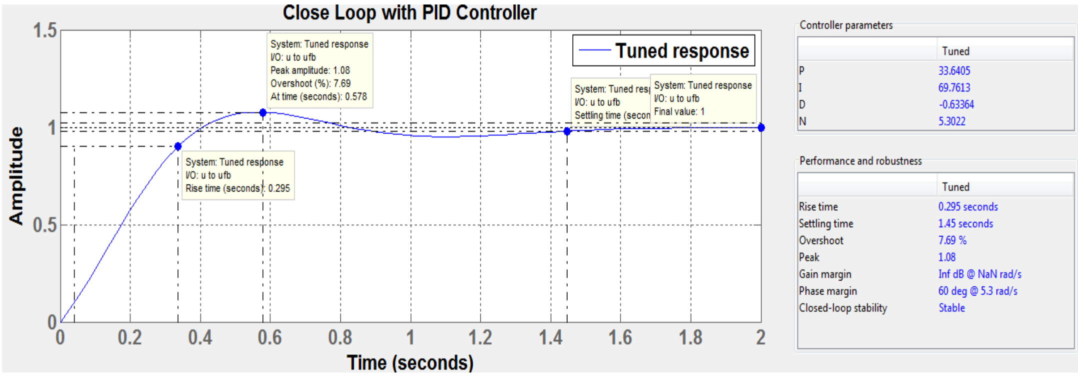
- No.2



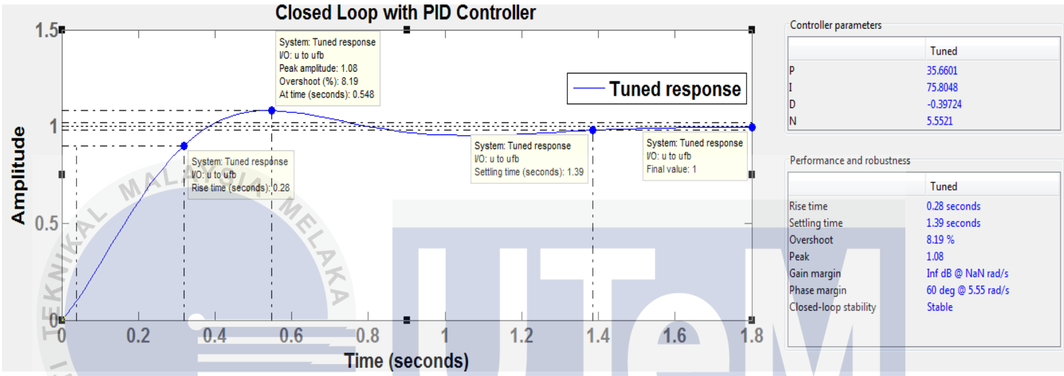
- No.3



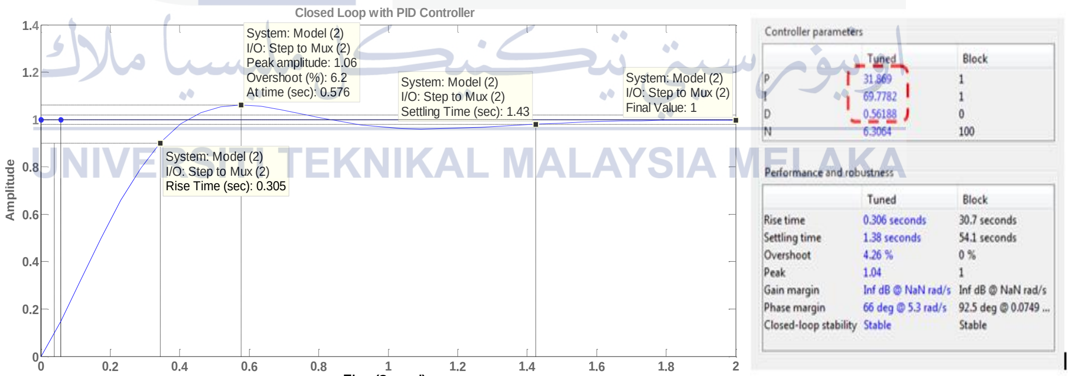
➢ No.4



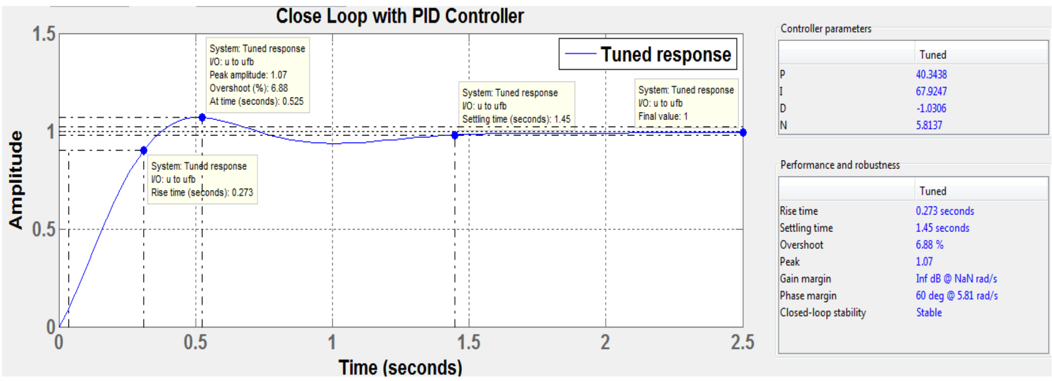
➢ No.5



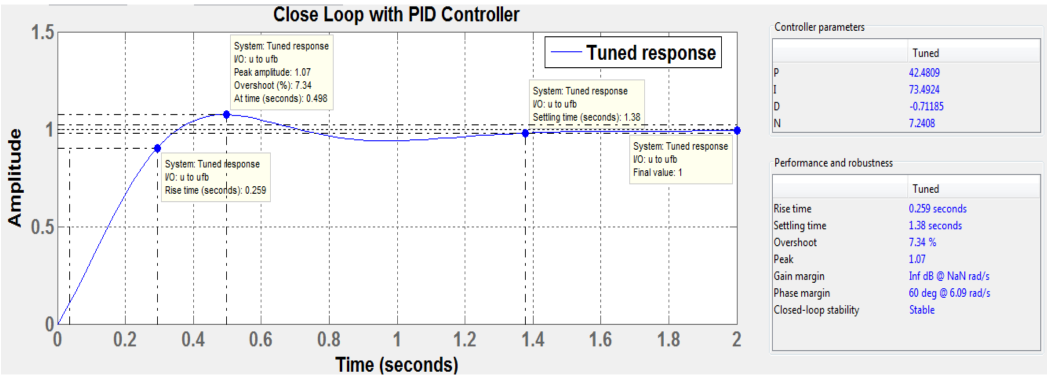
➢ No.6



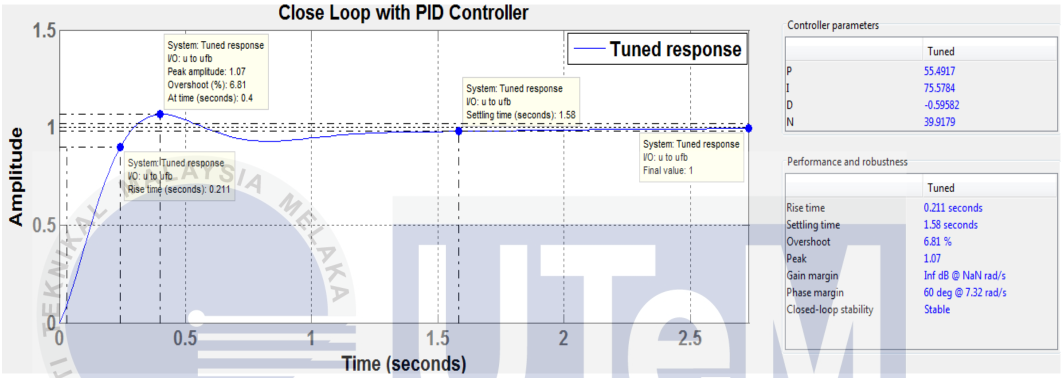
➢ No.7



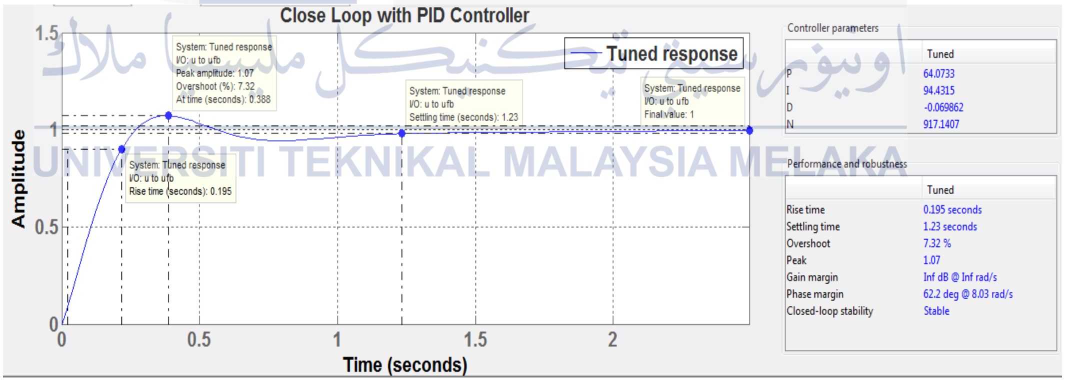
- No.8



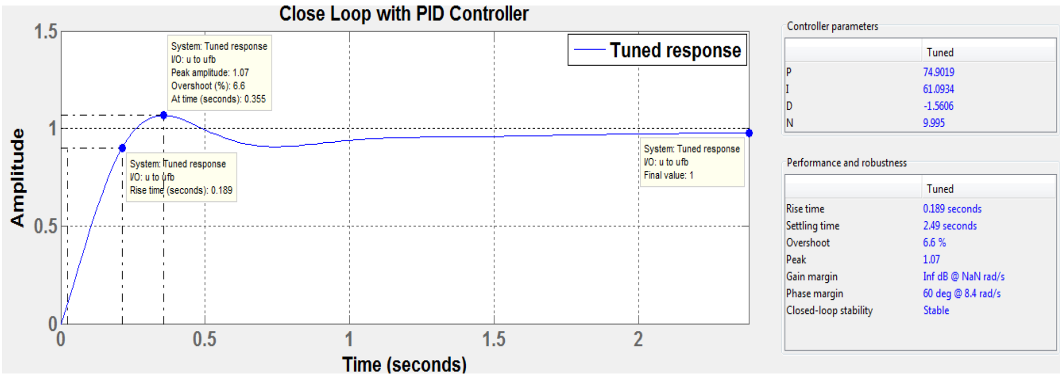
- No.9



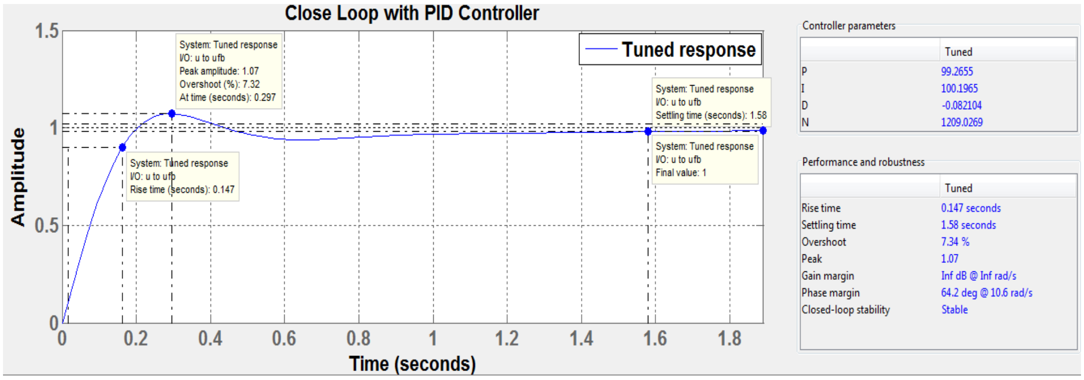
- No.10



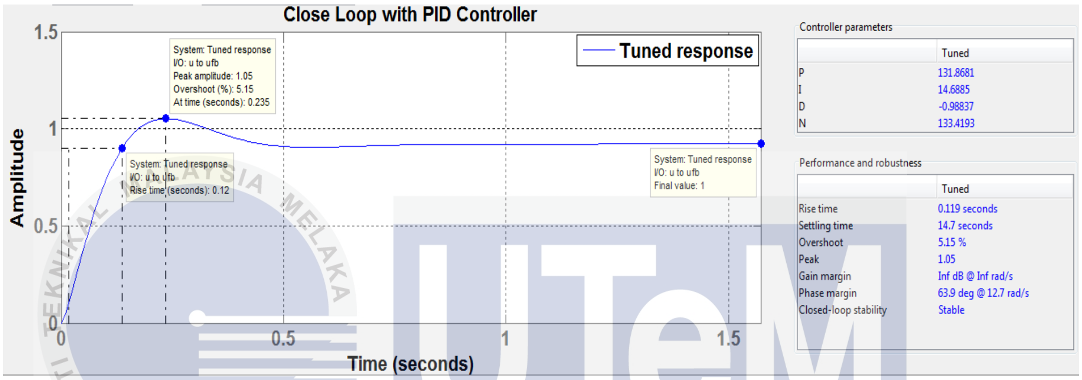
- No.11



- No.12


Close Loop with PID Controller
Tuned response
System: Tuned response
I/O: u to ufb
Peak amplitude: 1.07
Overshoot (%): 7.32
At time (seconds): 0.297
System: Tuned response
I/O: u to ufb
Rise time (seconds): 0.147
System: Tuned response
I/O: u to ufb
Settling time (seconds): 1.58
System: Tuned response
I/O: u to ufb
Final value: 1
Amplitude
Time (seconds)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0
0.5
1
1.5
Controller parameters
Tuned
P 99.2655
I 100.1965
D -0.082104
N 1209.0269
Performance and robustness
Tuned
Rise time 0.147 seconds
Settling time 1.58 seconds
Overshoot 7.34 %
Peak 1.07
Gain margin Inf dB @ Inf rad/s
Phase margin 64.2 deg @ 10.6 rad/s
Closed-loop stability Stable

- No.13


Close Loop with PID Controller
Tuned response
System: Tuned response
I/O: u to ufb
Peak amplitude: 1.05
Overshoot (%): 5.15
At time (seconds): 0.235
System: Tuned response
I/O: u to ufb
Rise time (seconds): 0.12
System: Tuned response
I/O: u to ufb
Final value: 1
Amplitude
Time (seconds)
0
0.5
1
1.5
0
0.5
1
1.5
Controller parameters
Tuned
P 131.8681
I 14.6885
D -0.98837
N 133.4193
Performance and robustness
Tuned
Rise time 0.119 seconds
Settling time 14.7 seconds
Overshoot 5.15 %
Peak 1.05
Gain margin Inf dB @ Inf rad/s
Phase margin 63.9 deg @ 12.7 rad/s
Closed-loop stability Stable

APPENDIX J

10) PID Controller in Arduino's Microcontroller

```
float sensorValue,voltage;
const int buttonPin = 2;
int buttonState = 0;
const int buttonPin1= 3;
int buttonState1 = 0;
int dummy = 0;

float actual,sp=0.21,error,previous_error,PID_controller,derivative=0,integral=0;
float kp=31.87,ki=69.78,kd=0.56;

#include <Stepper.h>
const int stepsPerRevolution = 200;
#define motorPin1 8
#define motorPin2 10
Stepper myStepper(stepsPerRevolution, 8,10);

void setup(){
  pinMode(buttonPin,INPUT);
  pinMode(buttonPin1,INPUT);
  myStepper.setSpeed(300);
  Serial.begin(9600);
   while (!Serial) {
    ; // wait for serial port to connect
   }
```

```
}


void loop(){


  sensorValue=analogRead(A0);
  voltage=0.0052*sensorValue;
   Serial.print("voltage ");
   Serial.print(voltage);
   Serial.println();
   delay(1000);


//error and apply with PID controller
  error=sp-voltage;


  if (error < 0){
    integral=(integral+error);
  }
  else{
    integral=0;
  }


  derivative=(error-previous_error);
  PID_controller= (error*kp)+(integral*ki)+(derivative*kd);
  Serial.println("PID_controller ");
  Serial.println(PID_controller);


    if ( error > 0){
```

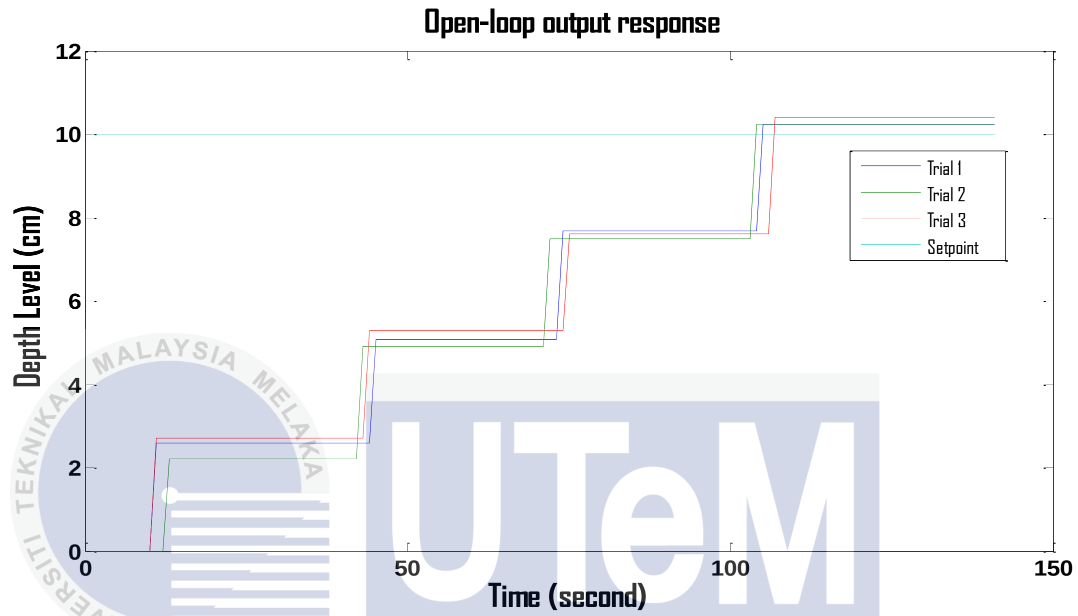
```
    Serial.println("Water In");
    myStepper.step(-2000*PID_controller);
    Serial.println();
    delay(0);
   }
     if (error < 0){
    Serial.println("Water Out");
    myStepper.step(-100*PID_controller);
    Serial.println();
    delay(0);
   }
   if (error = 0) {
    Serial.println("Stop");
    myStepper.step(0);
    Serial.println();
    delay(0);
   }
 // remember the previous value of the sensor
  previous_error=error;
}
```

APPENDIX K

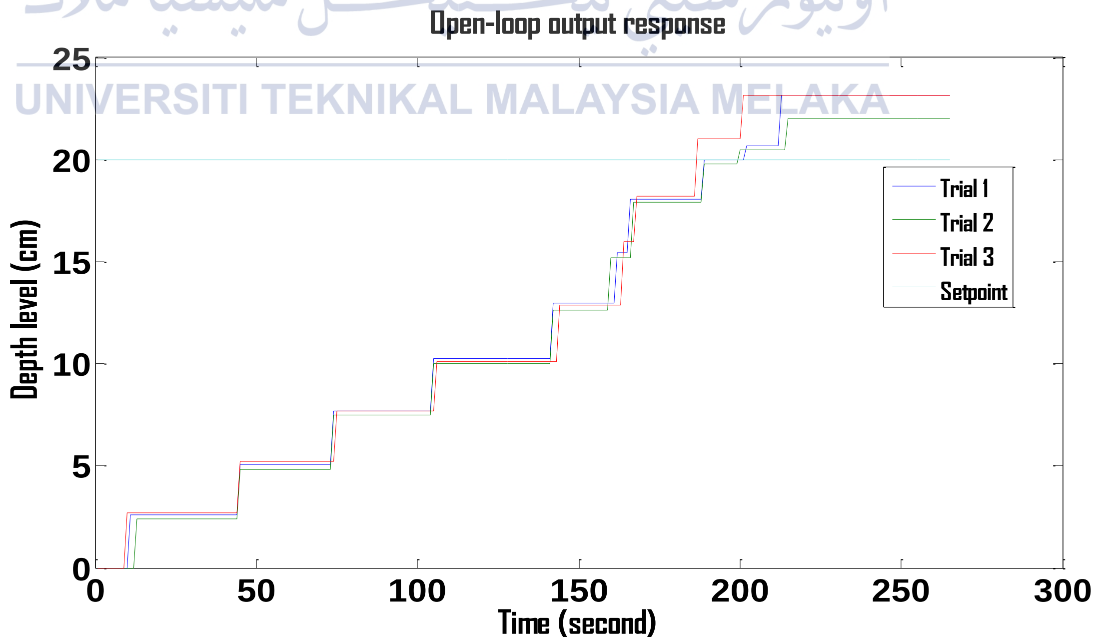
11) Testing and Analysis Operation of Ballast Tank

i) Open Loop System

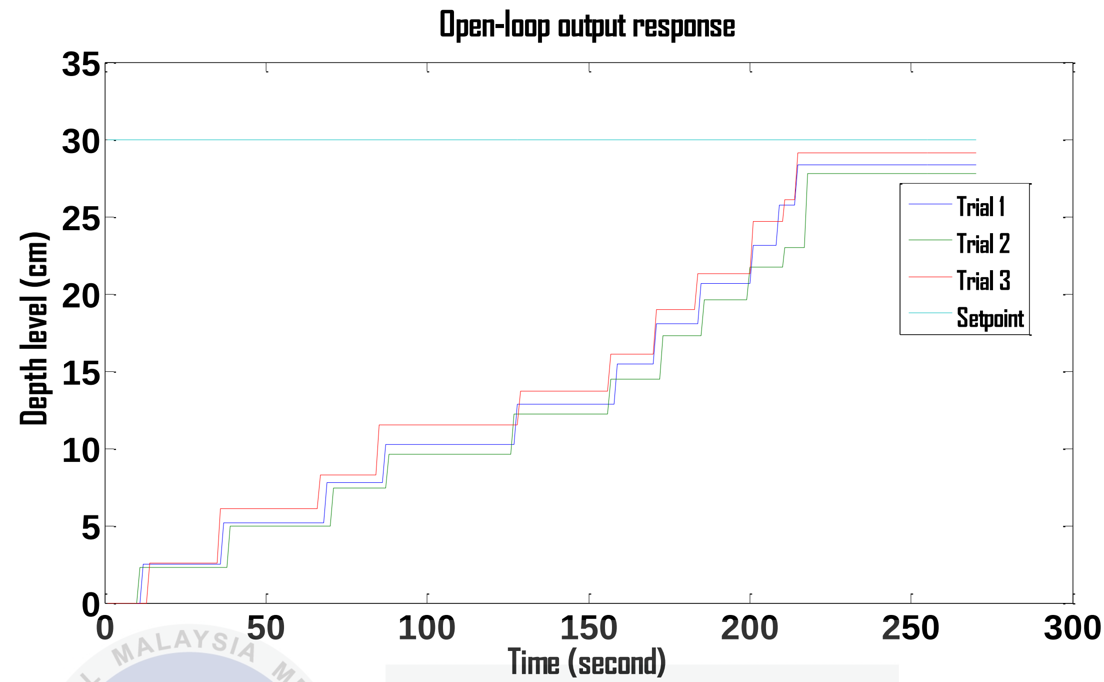
- Setpoint 0.19 V = 10 cm



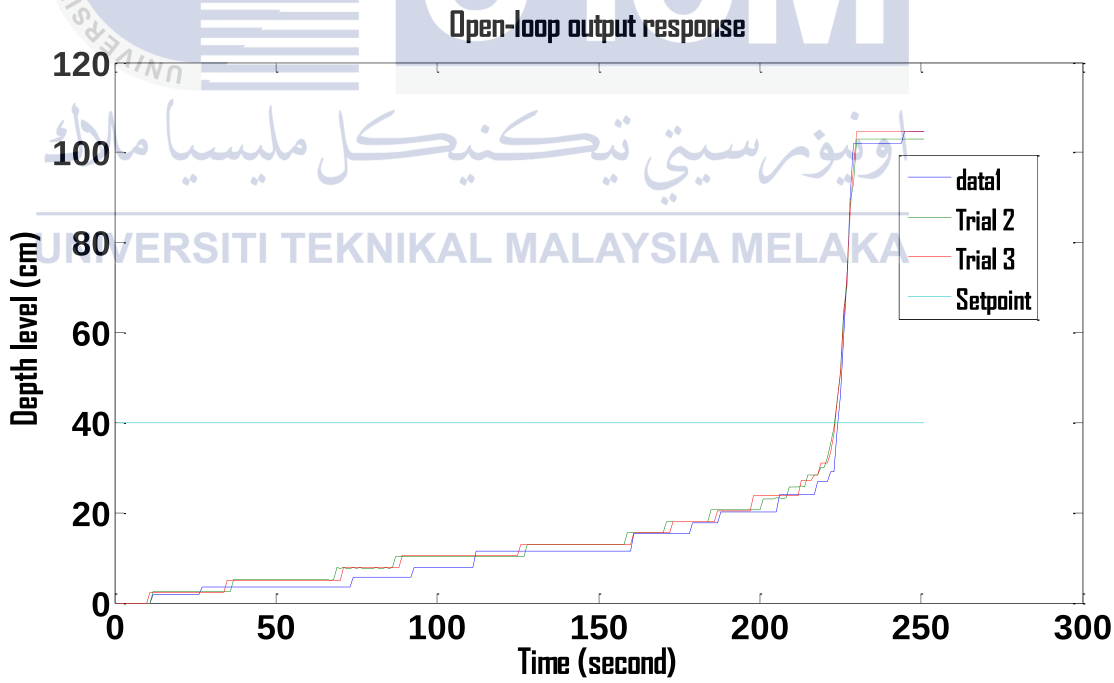
- Setpoint 0.21 V = 20 cm



➢ Setpoint 0.22 V = 30 cm

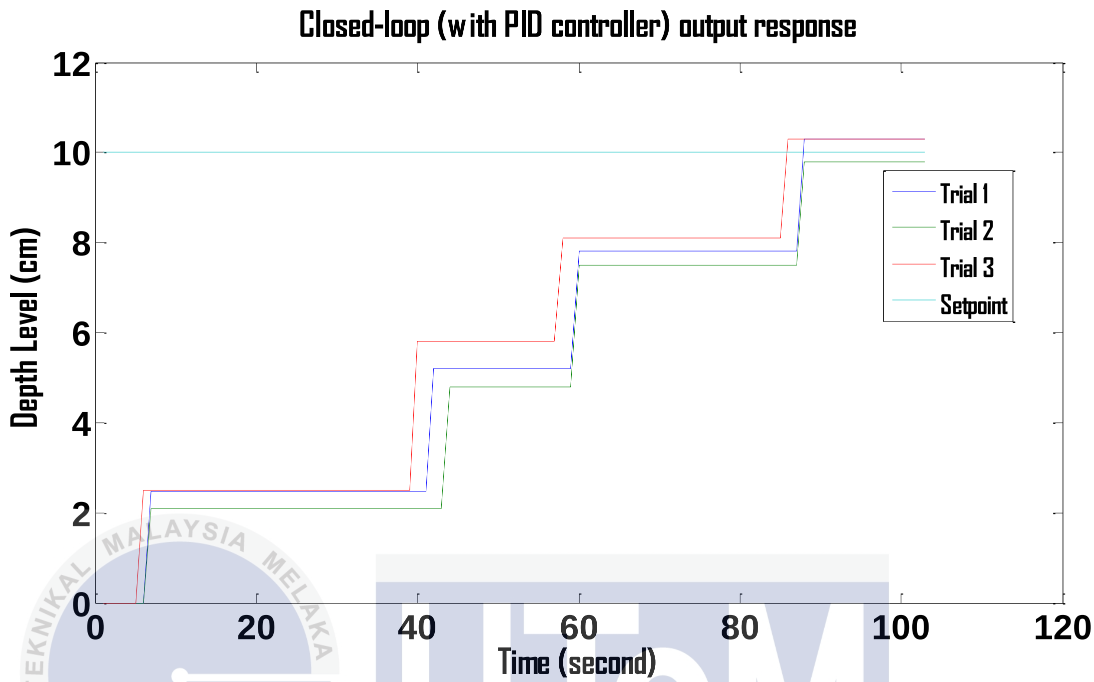


➢ Setpoint 0.24 V = 40 cm (***Limitation)

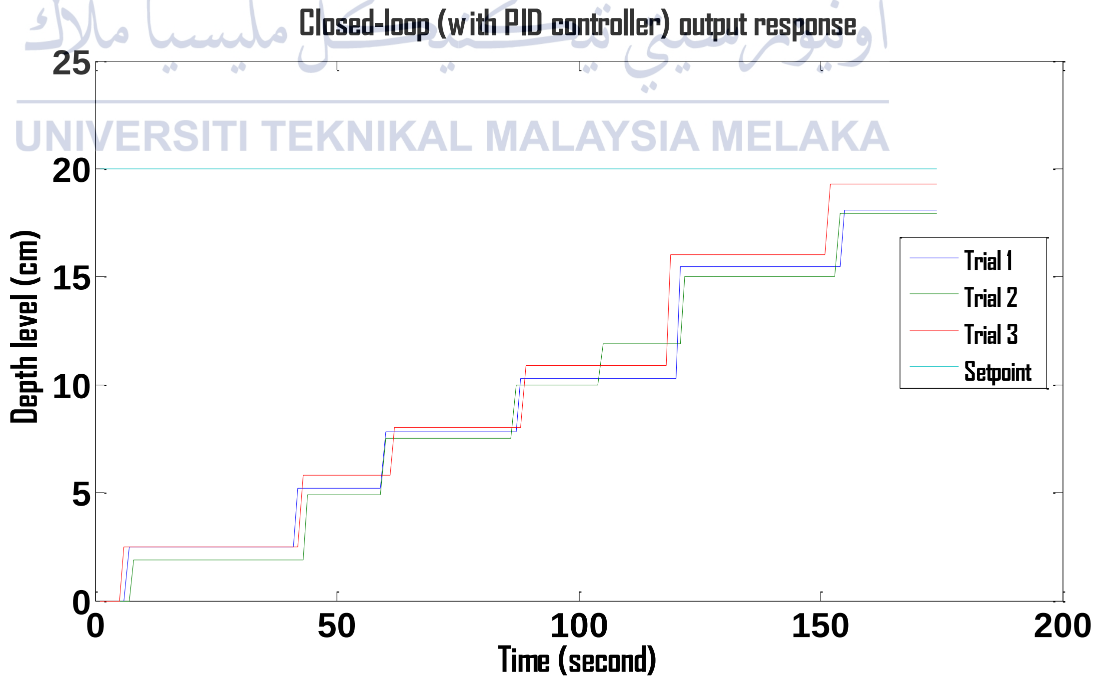


ii) Closed Loop System

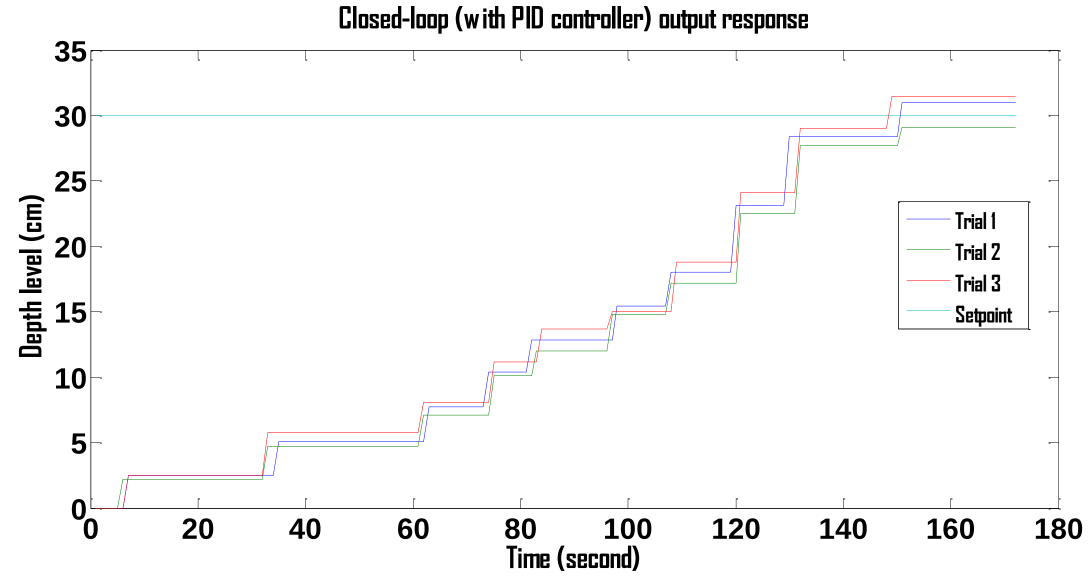
➢ Setpoint 0.19 V = 10 cm



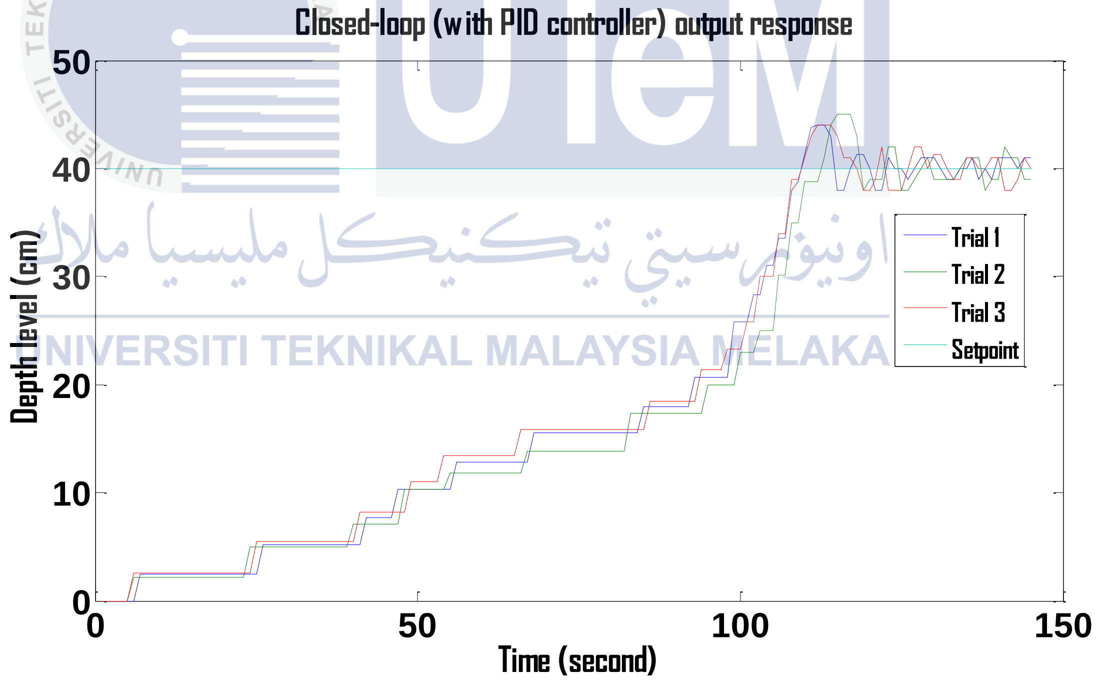
➢ Setpoint 0.21V = 20 cm



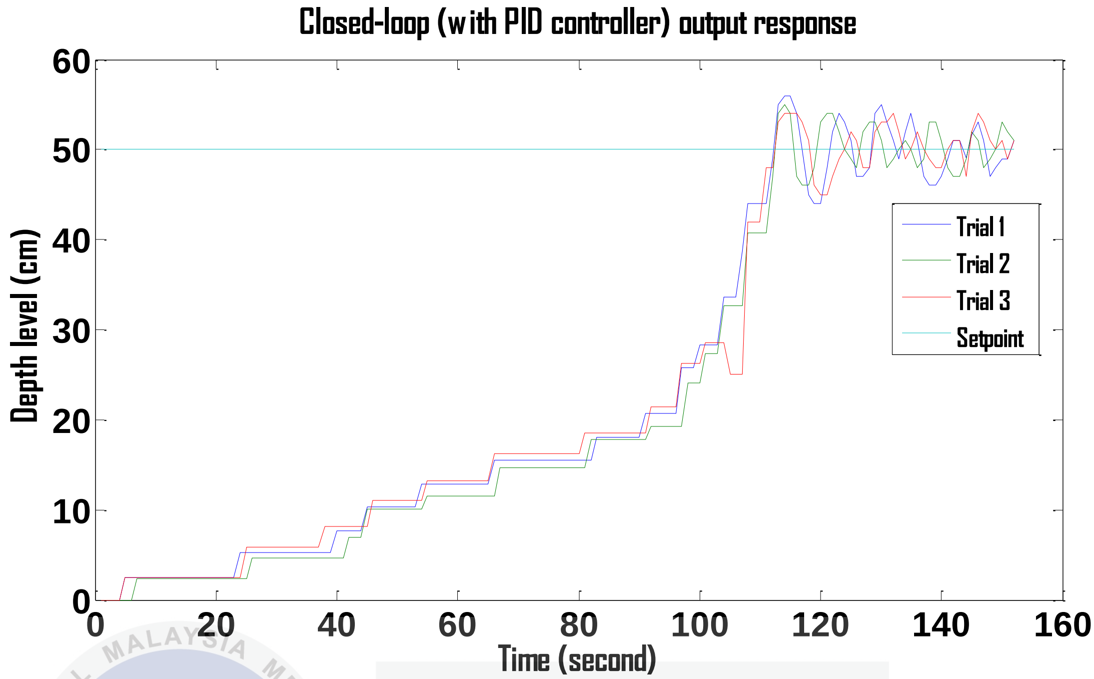
➢ Setpoint 0.22 V = 30 cm



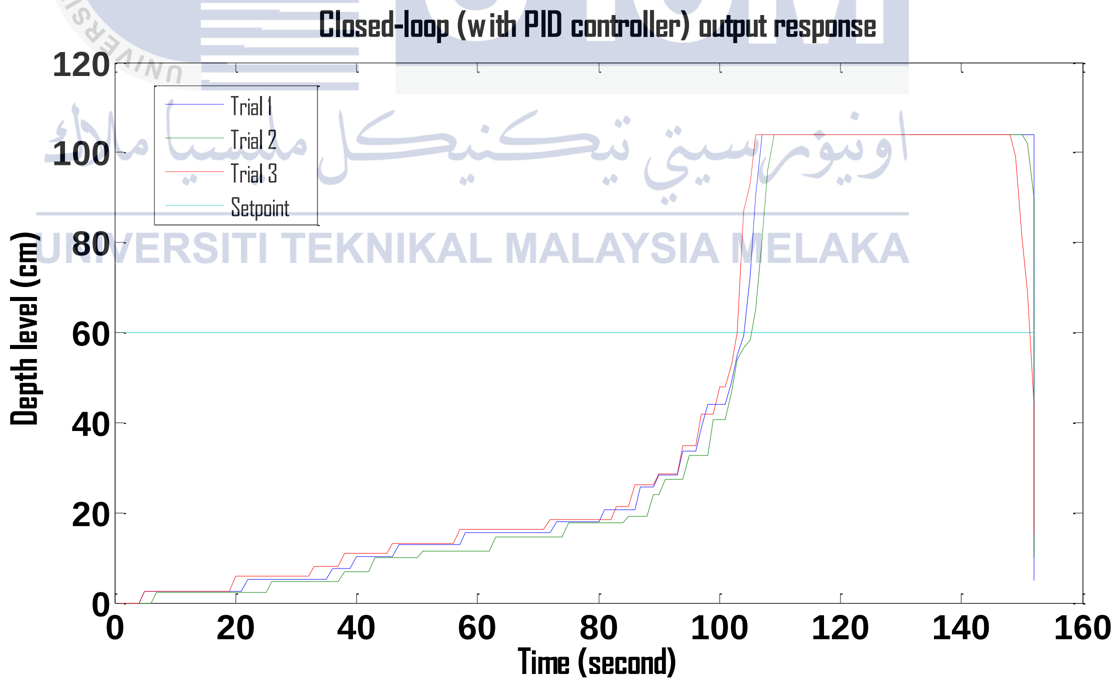
➢ Setpoint 0.24 V = 40 cm



- Setpoint 0.26 V = 50 cm



- Setpoint 0.27V = 60cm (***Limitation)

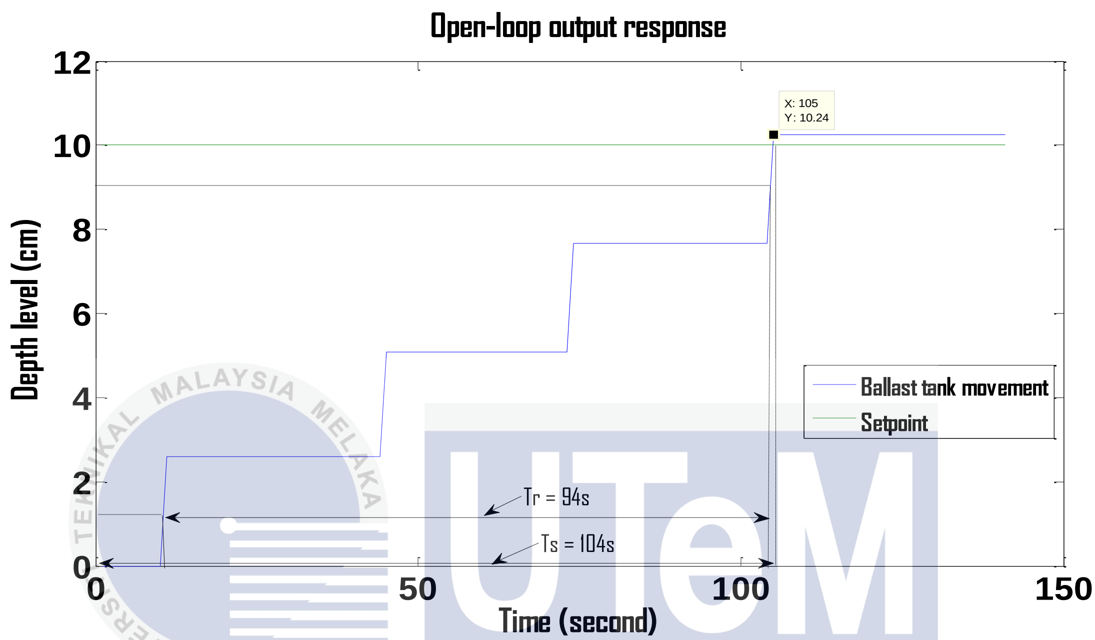


APPENDIX L

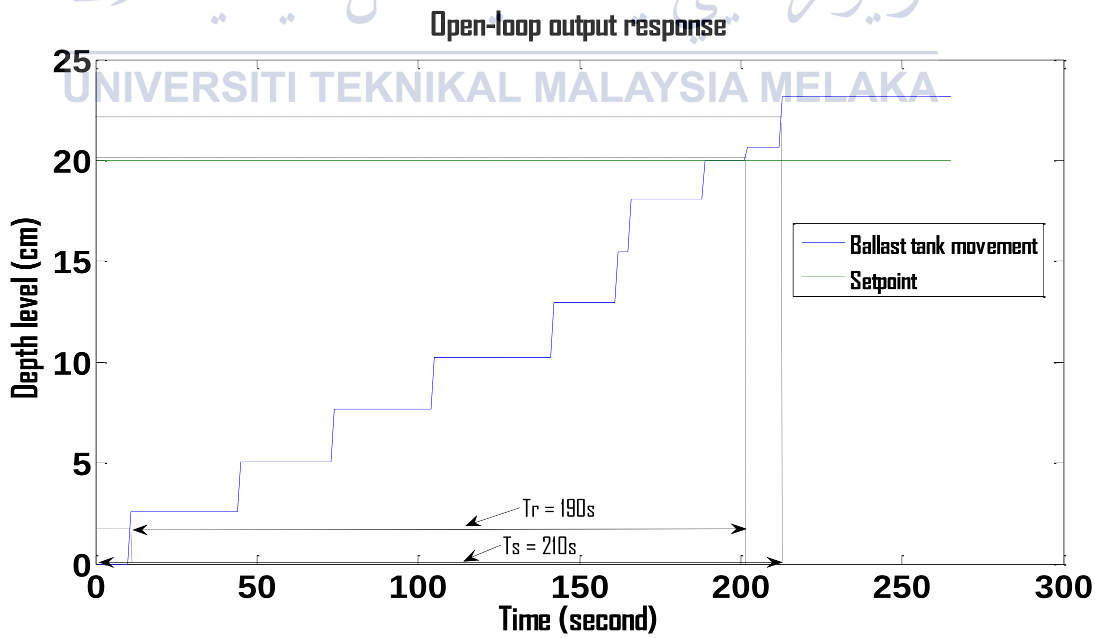
12) Performance (Rise Time and Settling Time) of the Ballast Tank

i) Open Loop System

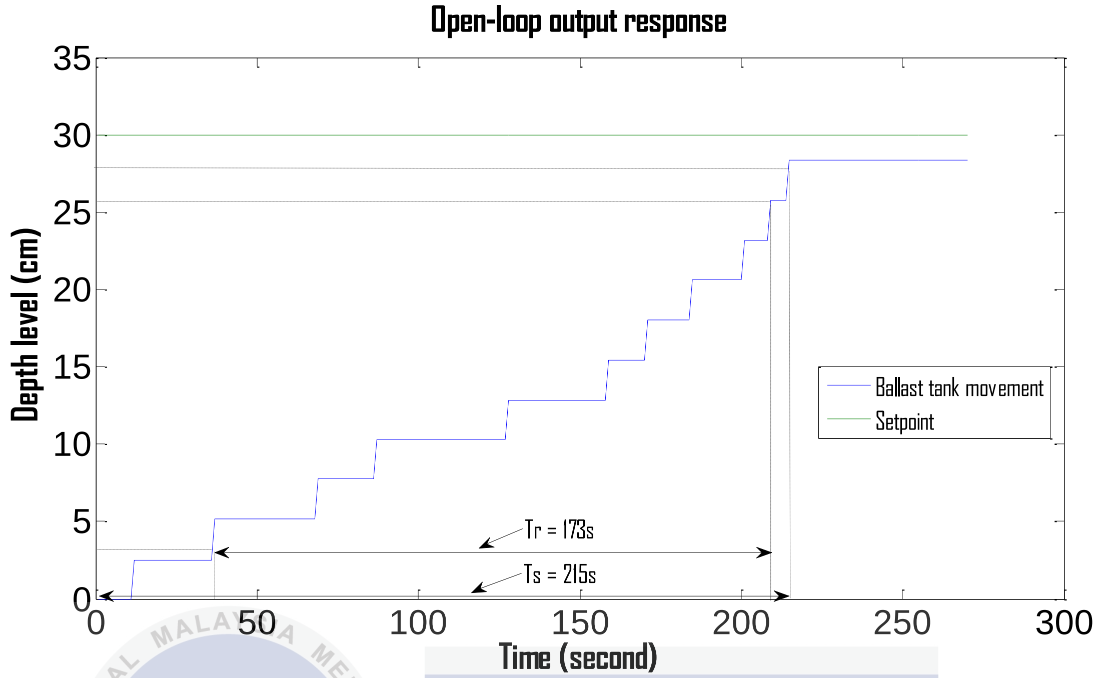
- Setpoint 0.19 V = 10 cm



- Setpoint 0.21 V = 20 cm

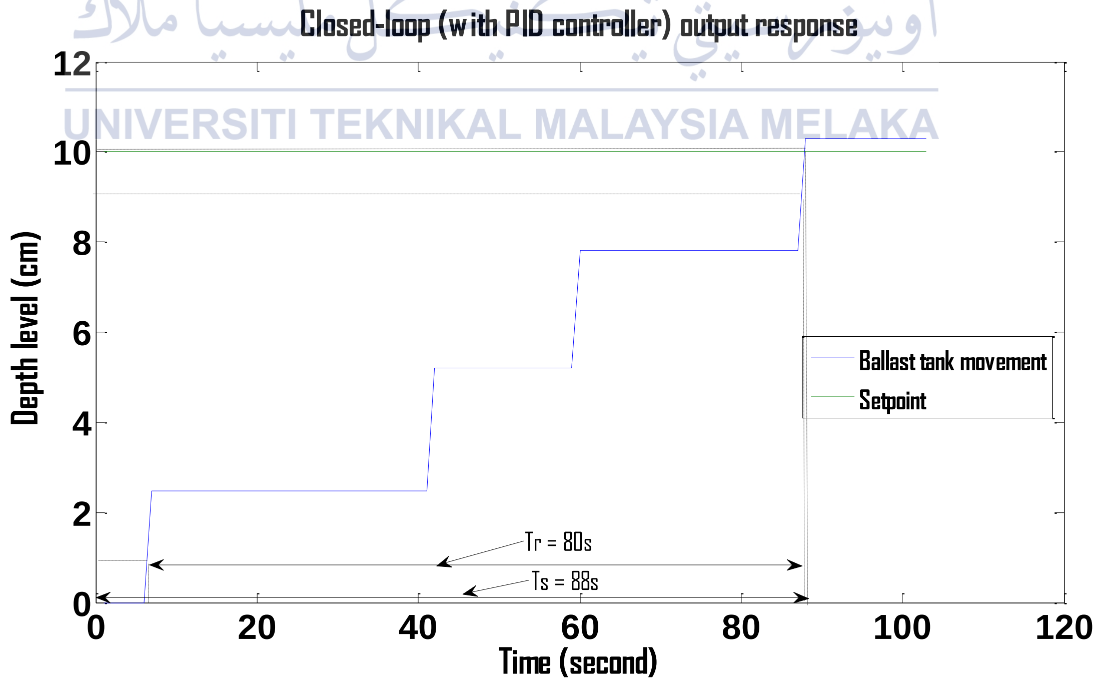


➢ Setpoint 0.22 V = 30 cm

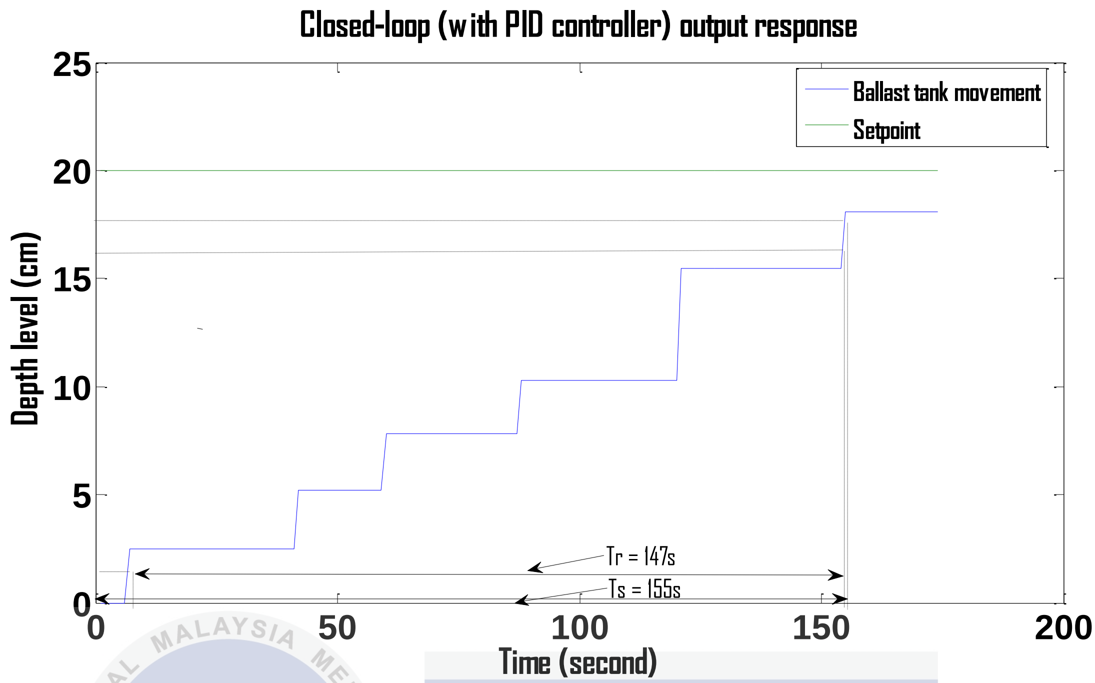


ii) Closed Loop System

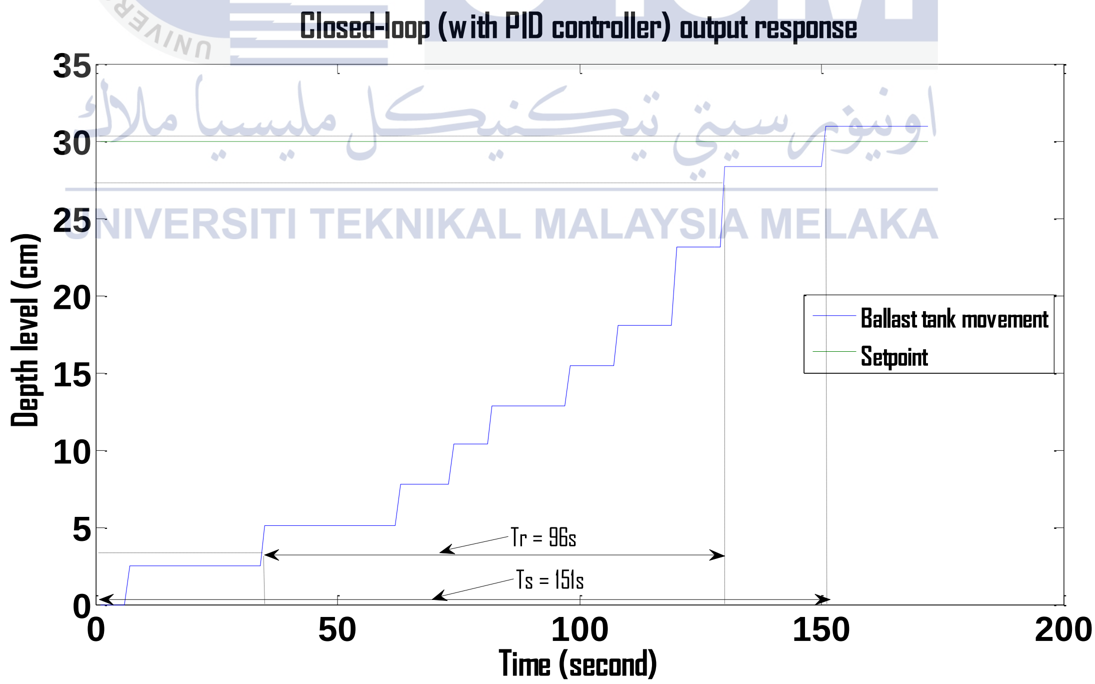
➢ Setpoint 0.19 V = 10 cm



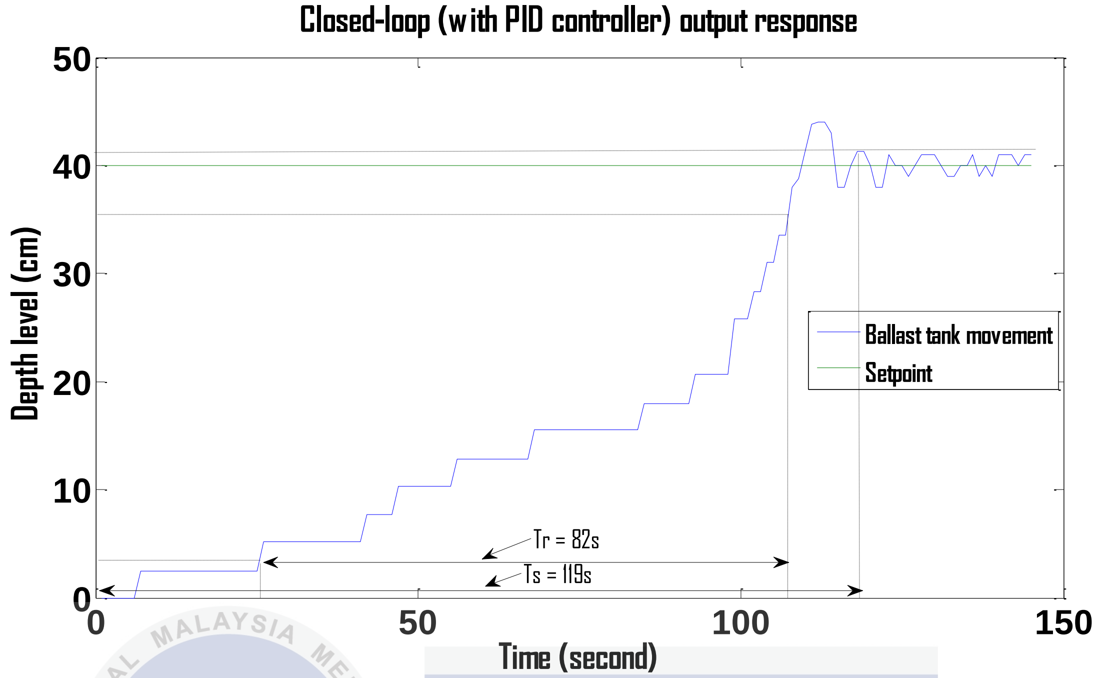
➢ Setpoint 0.21 V = 20 cm



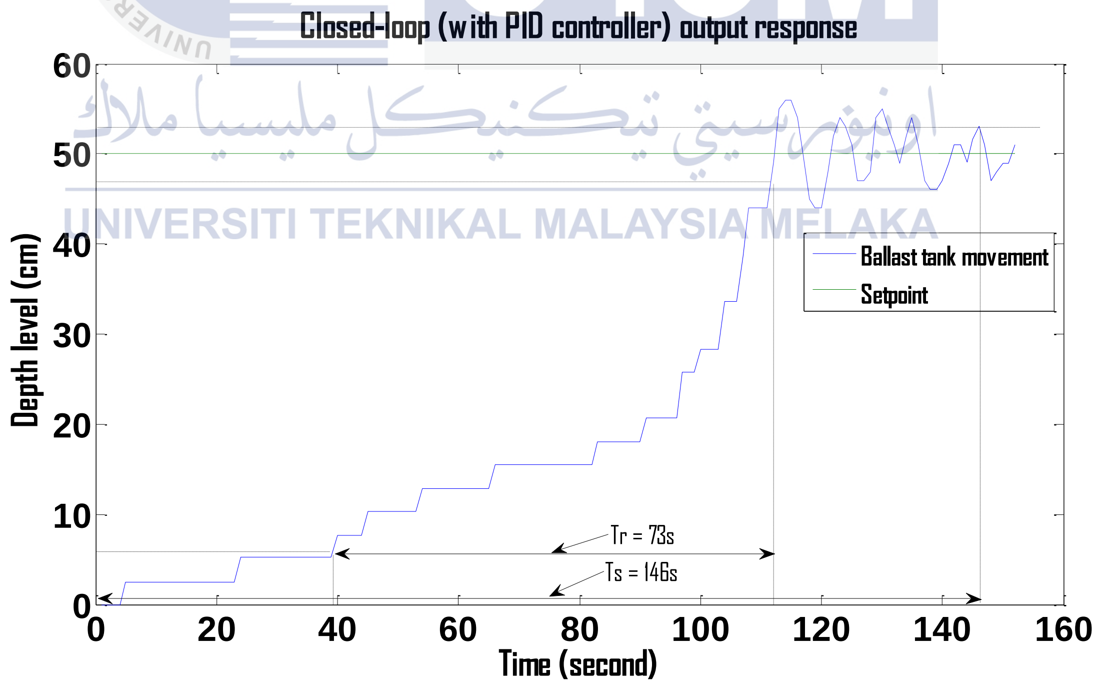
➢ Setpoint 0.22 V = 30 cm



- Setpoint 0.24 V = 40 cm



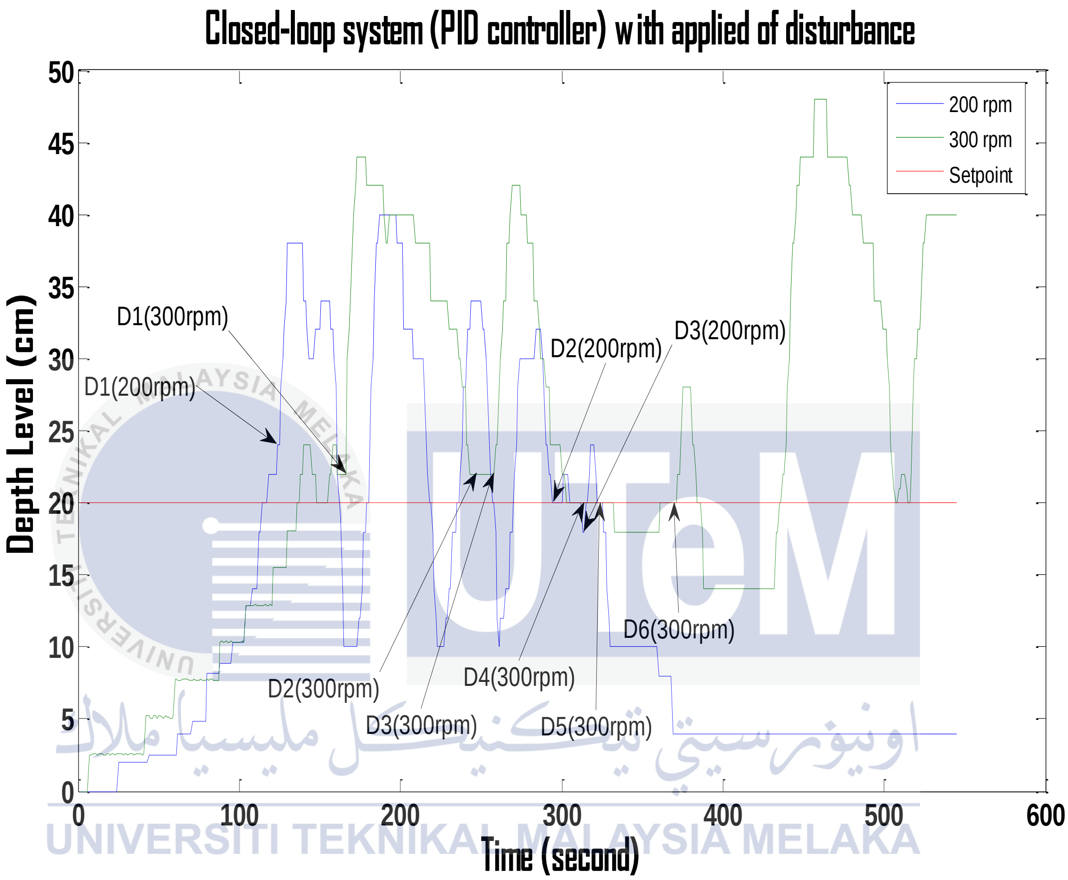
- Setpoint 0.26 V = 50 cm



APPENDIX M

13) Close Loop with Applied of Disturbance

- Setpoint 0.21 V = 20 cm

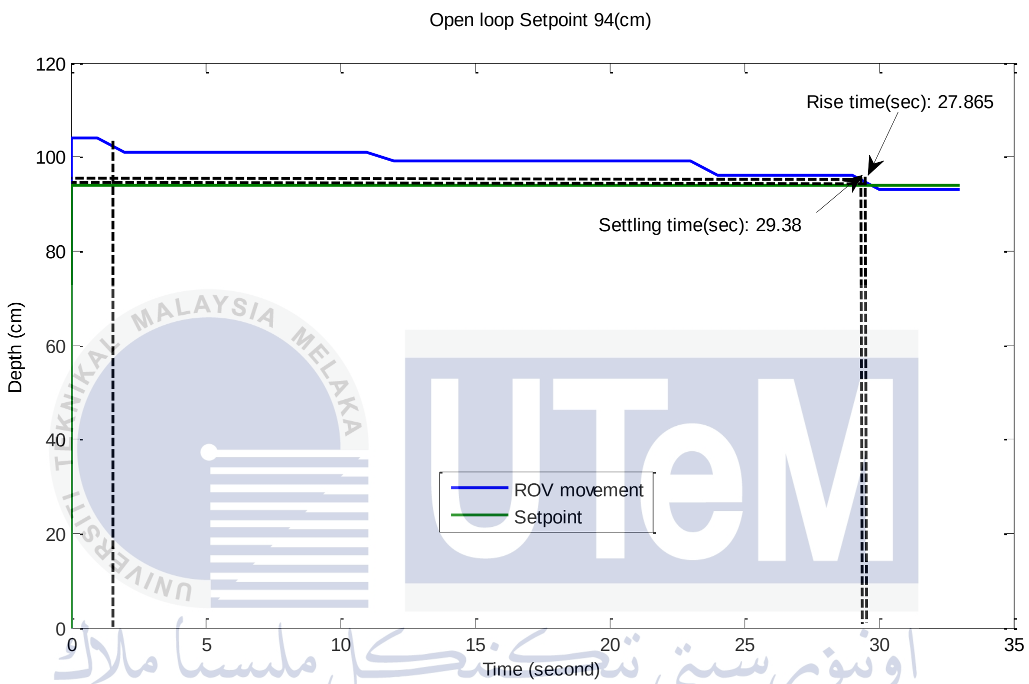


APPENDIX N

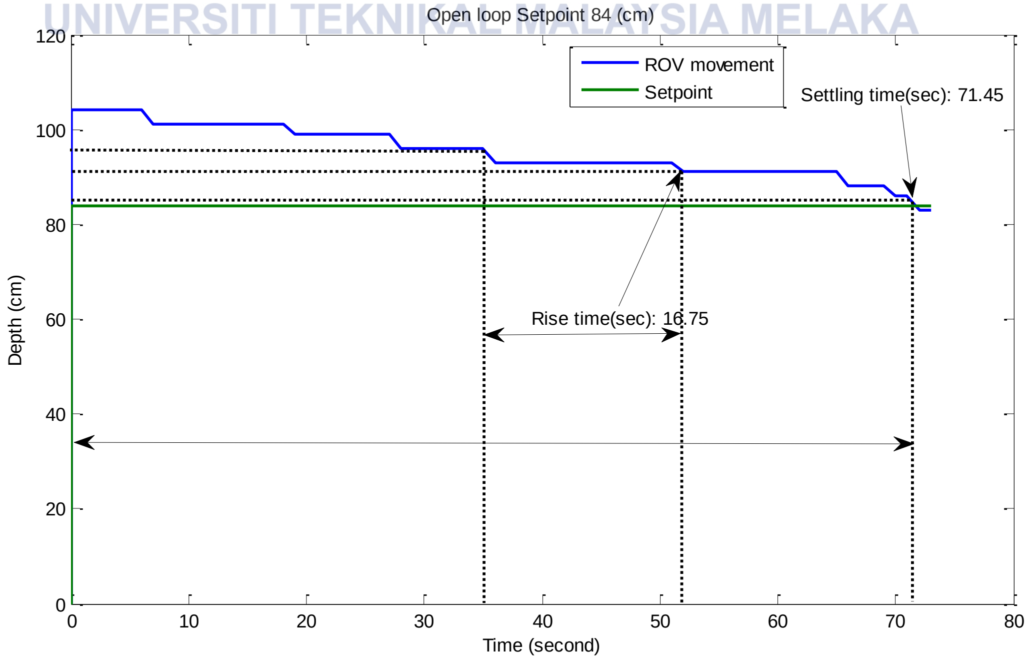
14) System Control Level from Bottom

i) <u>Open loop system</u>

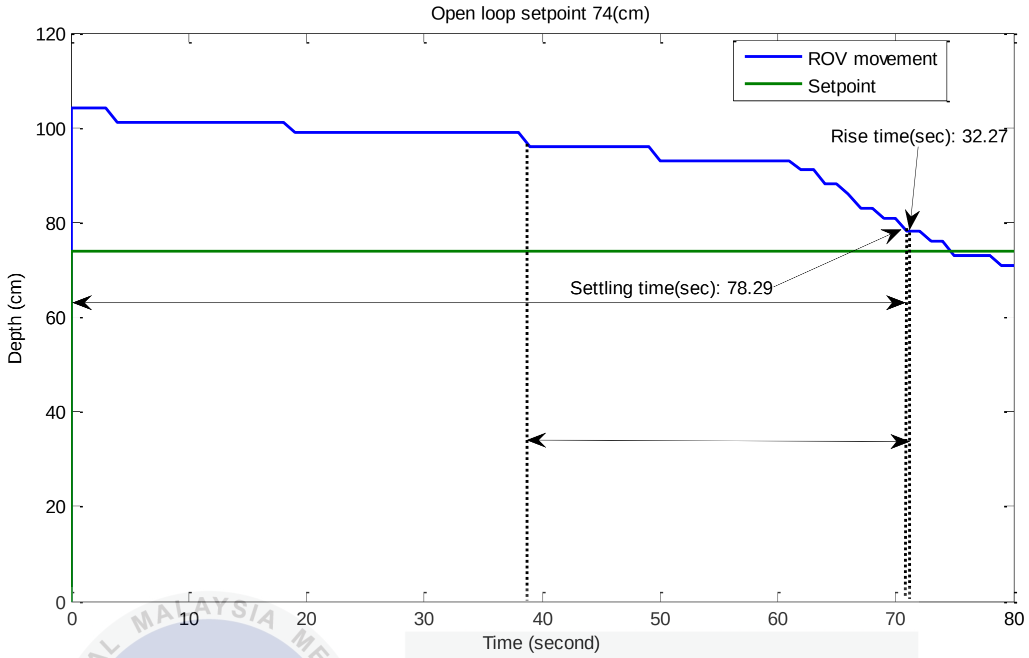
- **Setpoint 94 cm**



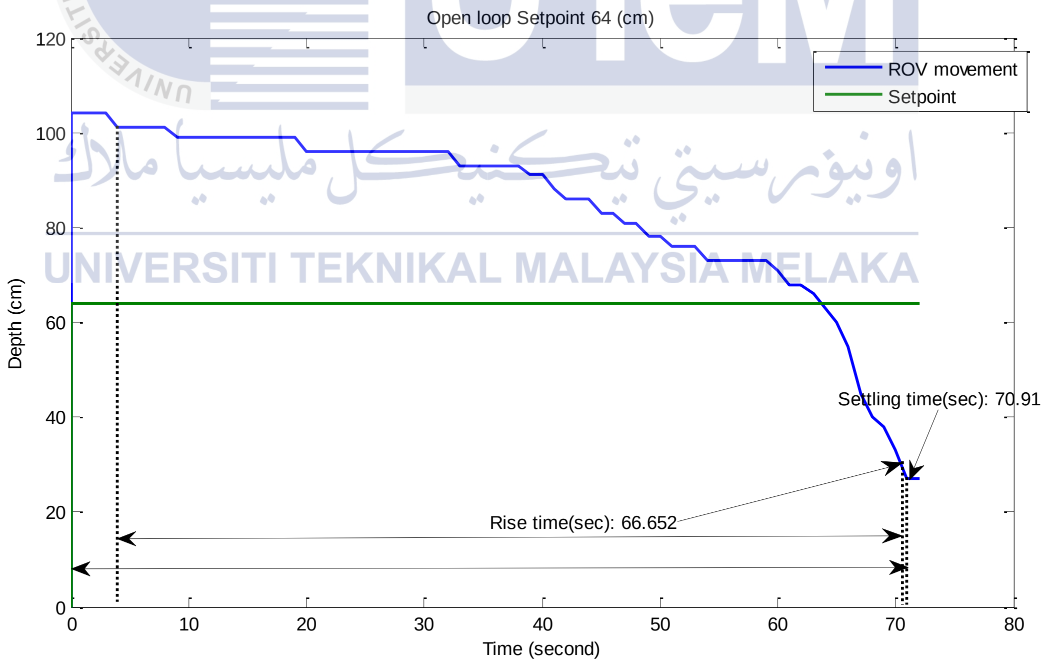
- **Setpoint 84 cm**



- **Setpoint 74 cm**

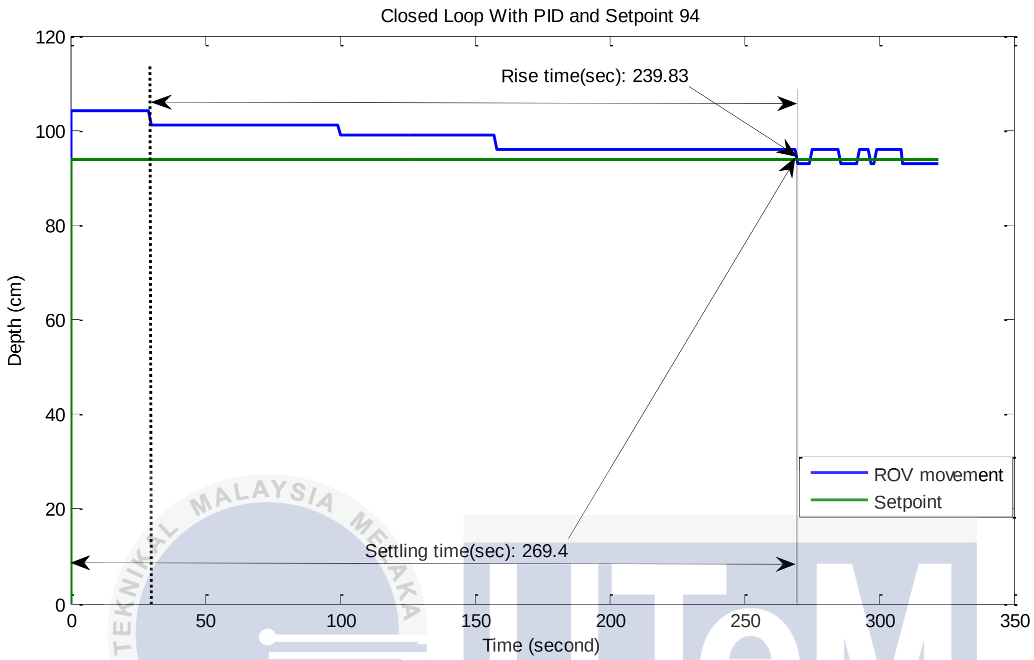


- **Setpoint 64 cm**

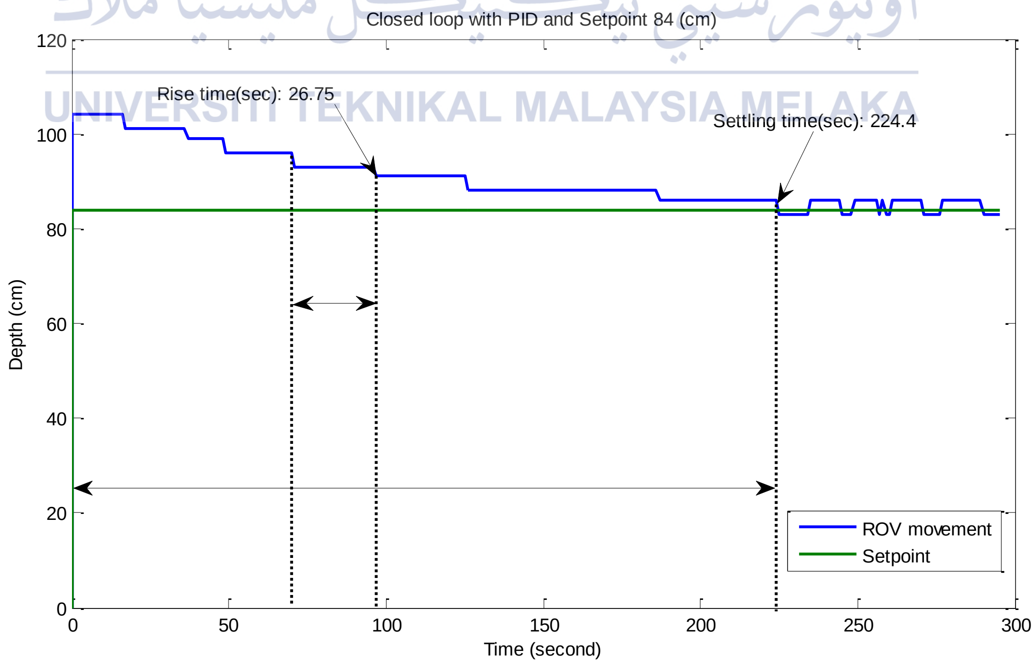


ii) Closed Loop System

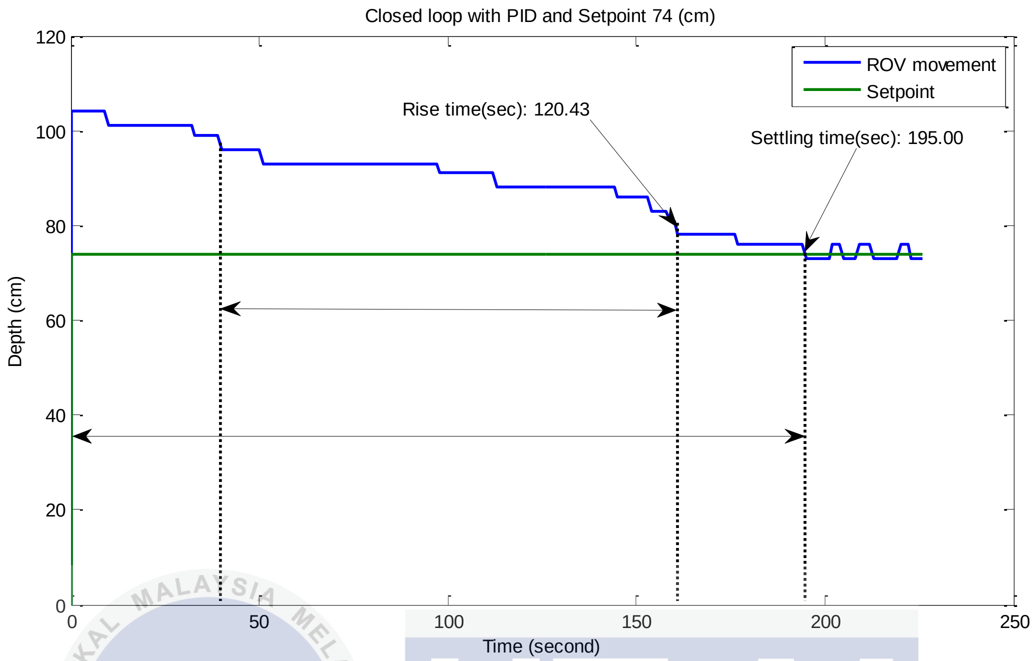
➢ Setpoint 94 cm



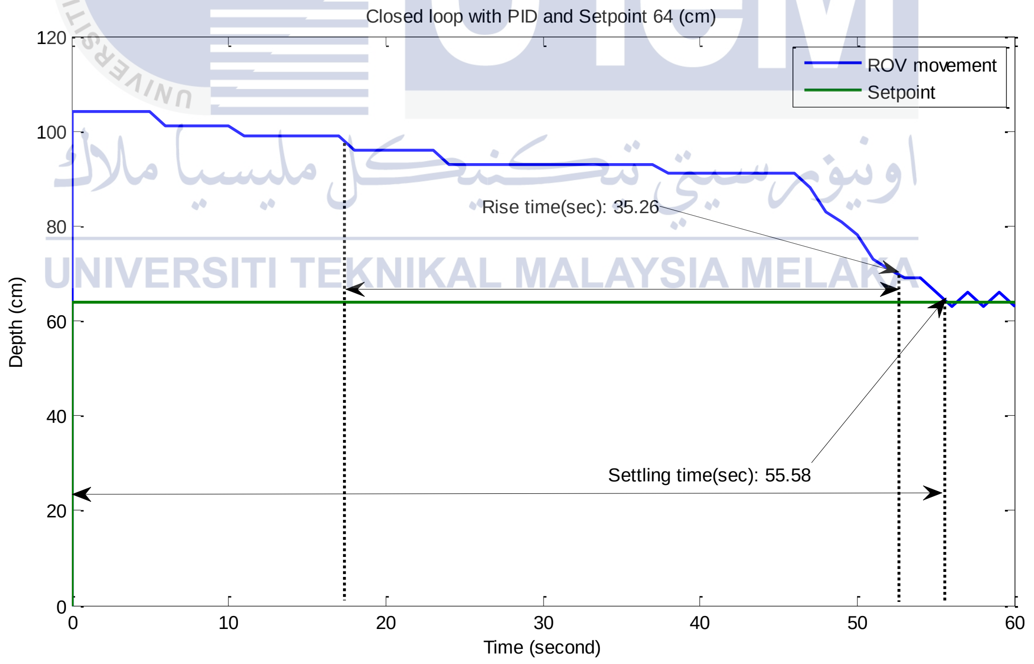
➢ Setpoint 84 cm



- **Setpoint 74 cm**



- **Setpoint 64 cm**



➢ **Setpoint 54 cm**