DESIGN AND DEVELOPMENT OF AN AUTONOMOUS UNDERWATER VEHICLE (AUV)

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A report submitted in partial fulfilment of the requirements for the degree of Bachelor of Mechatronics Engineering

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2016/2017

"I hereby declare that I have read through this report entitle "**Design and Development of an Autonomous Underwater Vehicle (AUV)**" and found that it has comply the partial fulfilment for awarding the degree of Bachelor of Mechatronics Engineering.

Signature : ....

Supervisor's Name : DR. MOHD SHAHRIEEL BIN MOHD ARAS

Date : ....

I declare that this report entitle "**Design and Development of an Autonomous Underwater Vehicle (AUV)**" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : TAN WEI CHIANG

Date : ....

To my beloved mother and father

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First of all, I, Tan Wei Chiang as an undergraduate student from Universiti Teknikal Malaysia Melaka (UTeM) would like to express my greatest appreciation and deepest gratitude to my supervisor, Dr. Mohd Shahrieel Bin Mohd Aras for his patient guidance, professional training, encouragement and valuable advice during this FYP. His methodical approach to problem solving and encouraging words always filled me with optimism, energy and enthusiasm. Since his leadership and guidance made it a great learning experience for me.

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ABSTRACT

In underwater field, Remotely Operated Vehicle (ROV) and Autonomous Underwater Vehicle (AUV) are created to help human do marine research. AUV is an unmanned or fully sensors robotic vehicle that is using high technology to bring new capabilities to work in the subsea environment. One of the problems facing by AUV is the depth control since it may loss during surveillance because autonomously navigate in the sea. Thus, this project focused on the design and development of a low cost AUV with small size and high performance with its depth control. AUV need to be in small size to ease the mobility of the AUV when it performs tasks. Different speed will be used to test and evaluate the depth control since the depth also influenced by its speed. In designing the AUV, SolidWorks software is used and undergoes various simulation tests such as stress and strain test and stability by referring the center of mass. Next, the hardware that discussed and selected included frames, hull, enclosure box, propulsion and submersion that achieve a certain performance in terms of reliability and controllability. This project uses pressure sensor MPX5700AP as depth control to determine the depth of AUV submersion. AUV uses an AfroESC 30A to control the speed for Blue Robotics T200 thruster to move it along vertical and horizontal axis that automatic operate based on the programming coding. In this project, the scope of the study focused on the interface between mechanical and electrical design with the small size (70cm X 50cm X 30cm) made of acrylic that waterproof and the submerge range of depth in between 2 to 6 meters. The AUV is going to undergo a series of field test at the end to evaluate its ability and performance in the swimming pool task.

ABSTRAK

Dalam bidang bawah air, kenderaan kawalan jauh (ROV) dan kenderaan bawah air (AUV) yang dicipta untuk membantu manusia melakukan penyelidikan marin. AUV adalah kenderaan robotik tanpa pemandu atau sensor sepenuhnya yang menggunakan teknologi tinggi untuk membawa keupayaan baru untuk bekerja dalam persekitaran dasar laut. Salah satu masalah yang dihadapi oleh AUV adalah kawalan kedalaman kerana ia boleh kehilangan semasa pengawasan kerana autonomi mengemudi di laut. Oleh itu, projek ini memberi tumpuan kepada penciptaan dan pembuatan AUV yang kos rendah dengan saiz kecil dan berprestasi tinggi dengan kawalan kedalaman. AUV perlu direka dengan saiz kecil supaya memudahkan mobiliti AUV semasa ia melaksanakan tugas. Kelajuan yang berbeza digunakan untuk menguji dan menilai kawalan kedalaman kerana ia mempengaruhi kedalaman. Dalam mereka AUV, perisian Solidworks digunakan dan kemudian menjalankan pelbagai ujian simulasi terhadap AUV seperti ujian tekanan dan kestabilan dengan pusat jisim. Seterusnya, perkakasan yang dibincangkan dan dipilih termasuk rangka, badan kapal, kotak kepungan, pendorongan dan penenggelaman yang mencapai prestasi yang tertentu dari segi kebolehpercayaan dan keupayaan pengawalan. Projek ini menggunakan pengesan tekanan MPX5700AP untuk kawalan kedalaman bagi menentukan kedalaman AUV semasa menyelam. AUV menggunakan AfroESC 30A untuk mengawal kelajuan T200 penujah supaya bergerak sepanjang paksi menegak dan mendatar yang automatik beroperasi berdasarkan pengaturcaraan. Dalam projek ini, skop kajian memberi tumpuan kepada reka bentuk mekanikal dan elektrik dengan saiz kecil (70cm X 50cm X 30cm) diperbuat daripada akrilik yang berkalis air dan kedalaman di antara 2 hingga 6 meter. AUV akan menjalani satu siri ujian pada akhirnya untuk menilai keupayaan dan prestasinya dalam tugas-tugas yang disediakan di dalam kolam renang.

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LIST OF ABBREVIATION

UTeM	-	Universiti Teknikal Malaysia Melaka
AUV	-	Autonomous Underwater Vehicle
ROV	-	Remotely Operated Vehicle
OOS	-	Ocean Observation System
UUV	-	Unmanned Underwater Vehicle
ONR	-	Office of Naval Research
MIT	-	Massachusetts of Washington
USM	-	Universiti Sains Malaysia
IMU	-	Inertial Measurement Unit
CAD	-	Computer-Aided Design
COM	-	Center of Mass

CHAPTER 1

INTRODUCTION

1.1 Introduction

Generally, Unmanned Underwater Vehicles (UUV) have been designed and developed in various countries, including Malaysia for the past ten years in marine technology. It can be categorized into two forms which are Remotely Operated Vehicle (ROV) and Autonomous Underwater Vehicle (AUV) with the almost the same function as shown in Figure 1.1. Figure 1.2 shows the classification of UUV. AUV is basically an extension of the ROV's technology. The ROV is controlled by the human from the controller and needs navigation control on the surface of the core ship, whereas the AUV is controlled by its on-board controller guided by build-in pre-programmed instructions with free from a chain [1-2]. The common AUV has a submarine or torpedo shape with a minimum of one thruster for forward, backward and rudders adjust left and right direction.

Figure 1.1: Types of Underwater Vehicle [1]

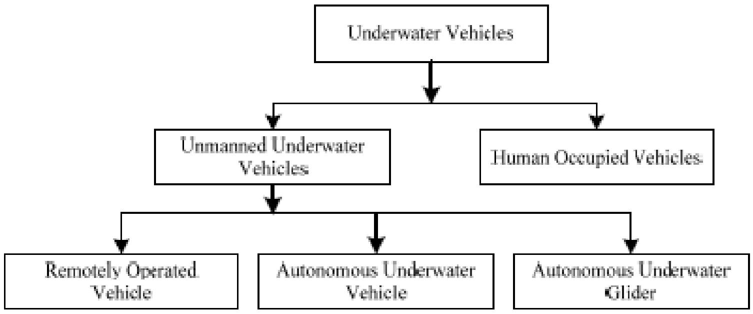


Figure 1.2: Classification of Underwater Vehicle [2]

Formerly, underwater vehicle has been used in a limited number of tasks. With further research and development, it able to reduces the limitation and increase the capability to do more tasks. Today, most of AUV can be seen in military field include mine detection, topography, search, observation mission, oiled and gas industry and some of the expeditions to explore under the deep sea as shown in Figure 1.3 [3].

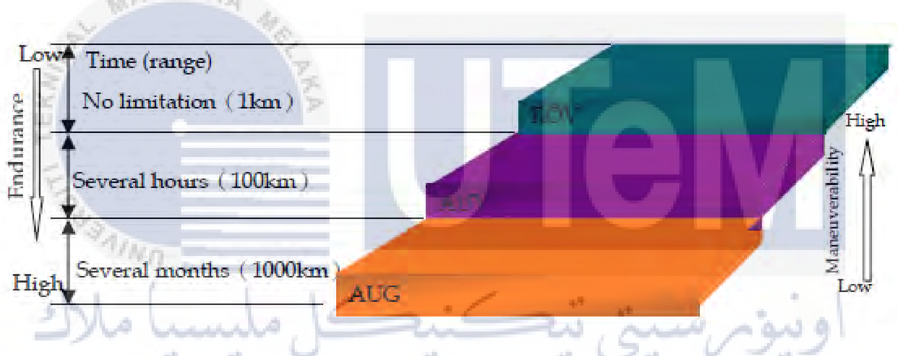


Figure 1.3: Performances of three Underwater Vehicles [3]

This project is getting more and more important that shows the design implementation of an AUV for a multiplicity of research test bed platform in underwater technologies [4]. In shallow water, the use of large AUV is not practical since the larger object has more inertia when moving around in the water and it is difficult to avoid obstacles. Thus, small AUV more suitable in shallow water to perform tasks due to its ease of mobility as well as compact without limiting its functionality and long lasting power [2].

This project focuses on mechanical design and depth controller for AUV. To complete this need to develop low cost AUV and fabrication for AUV in Underwater Technology Research Lab at UTeM. The subparts of developing an AUV are mechanical body construction, electrical and electronic circuit designing, AUV test run and report writing.

1.2 Motivation

In Malaysia, the underwater vehicle still not widely studied and investigated. Malaysia still considered far behind as compared to western countries due to some limitations like Ocean, underwater knowledge, high and efficient sensor technology. Western countries have many researchers, engineers and scientist who keeping design and develop unmanned vehicles for the underwater exploration purpose as shown in Figure 1.4. However, Malaysia still lack of knowledge and technology to carry out this AUV project.

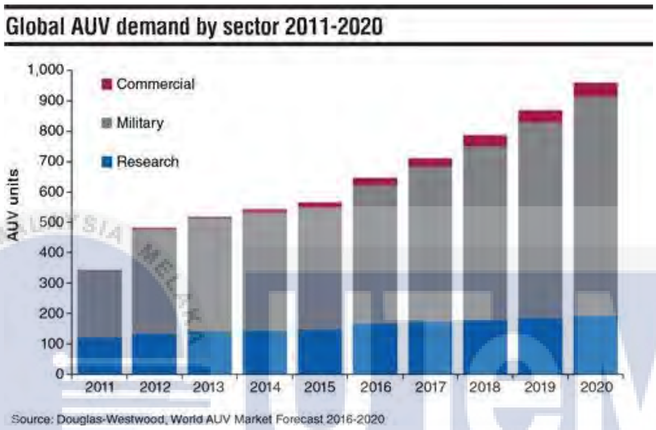


Figure 1.4: Forecast Global AUV demand by sector [4]

The ocean still has a lot of unidentified quantities which occupied approximately 71% of the surface of the Earth. So, there have many studies and growth about the underwater field include marine life environment and marine resources research and so on. The AUV investigation and navigation is not sufficient because underwater has low transparency and hard to observe the whole underwater life in detail [5].

Next, by referring to plane crashed case, MH370 which happen in the Indian Ocean. Malaysia needs to use technology from Australian country due to lack of technologies to detect splinter of the plane. Malaysia required to pay the commercial aid to relevant countries, while they actually used this chance to continue their further research [27].

Thus, the consequence of this project develops an AUV with low cost and good performance ready to join in any AUV competitions like Singapore AUV Challenge and Innovate. The project starts by design and fabricate following modifications, addition of basic sensor and common movement control.

1.3 Problem Statement

During the past few decades, a lot of engineers design and developed underwater vehicle to explore the depths of the deep sea and used in supervising marine environment and marine ocean life. Since the technology is getting an advance, integrated sensors AUV has been developing for advance growth in the military field by GPS and regulate the presence of mines in the seabed. Every 10m diving will raise one atmospheric pressure cause the water pressure stop from being stepped into the deep sea easily [6].

The AUV design is limited because the mechanical parts of AUV body must be strong enough to withstand the deep water pressure. Its body should be designed with hydrodynamic shape to ensure reduced the drag force exerted on it that will cause more power consumption. In Malaysia, the study of underwater technology lags behind western countries like USA, Russia, Japan and others. The tragedy MH370 submerge into Indian Ocean should be a warning to everyone about the importance of improving the technology in Malaysia [27].

AUV may loss during surveillance because autonomously navigate in the underwater seabed which is unpredictable and inherently dangerous. In depth motion control, AUV is particularly dangerous in vertical trajectory due to easier get inspected structure damage by crashing the bottom of the seabed. Thus, this project is developing to solve by improving the current AUV performance in terms of depth control and efficiency.

1.4 Objectives

Three objectives that required to achieved during this FYP;

1. To design and develop an AUV that able to float and submerge stabilized for underwater application.
2. To design a depth controller of the AUV at the desired depth with zero overshoot.
3. To study by evaluating and analysis the performance of an AUV in terms of maneuverability and movement.

1.5 Scope

The scopes and limitations of this project are:

a. The AUV is required in small size, dimension less than 70cm X 50cm X 50cm and lightweight less than 30Kg.

b. Power should be self-contained and tethers of any sort are not allowed.

c. The voltage of the power source used by each AUV should not exceed 24VDC.

d. AUV must be designed and developed with no danger of any kind to anyone or anything at the venue.

e. AUV has to swim underwater without surfacing or touching the bottom or wall.

f. The depth rating of the AUV is less than 3 meters from the water surface due to the limitation depth of a swimming pool and water leakage inside the hull.

g. The maximum duration for the AUV activity in underwater is 1 hour per cycle to prevent humidity hazards.

h. The microcontroller used is Arduino Mega, due to it has high processing power and up to 54 General Purpose Input Output pins.

i. Arduino Mega, MPX5700AP, 10 DOF IMU and ESC are tested for electronic sensor performance in underwater as shown in Figure 1.5.

j. 10 DOF IMU sensor is used as input for the tilt balancing mechanism of the AUV.

k. Increase the downward force (weight) acting on AUV to reduce the power used by thruster to submerge.

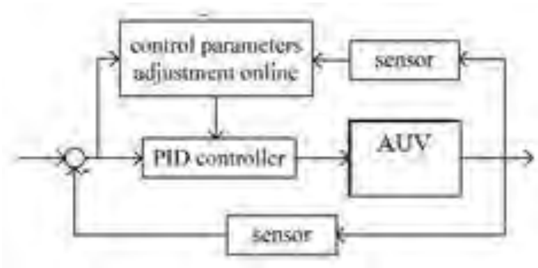


Figure 1.5: The Simple Block Diagram for AUV [3]

1.6 Organisation of Report

Chapter 2 is literature review which described the background theory which needed for this project. It also discussed the factors affecting an AUV followed by the mechanical design and electronic design. There are also the discussion and comparison between the previous AUVs project. For Chapter 3, methodology gives hardware in mechanical and electronic design and offerings the assembly AUV design chosen that were developed. There are comparisons between the shape and materials for mechanical parts.

Chapter 4 are results and discussion that described several simulations in the SolidWorks Xpress to help investigate the AUV. The simulation can be done through the SolidWorks toolbox to show the center of mass and stress-strain tests. Also, several tests on AUV in the swimming pool are to perform its performance. For Chapter 5, conclusion reviews the whole information in details for this project. There are also some suggestions for future work and recommendations.

1.7 Summary

This chapter concludes that the importance of an AUV in the water application. It summarized that the AUV platform is very limited because the requirement component specification is very critical like waterproof issue, imperfect accuracy and error. It focuses more on the new propulsion systems and batteries with high capacitance. The key to this enabling technology is the development of the optimum sensing and platform required, which are low cost, highly reliable, robust and environmentally friendly.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

It presents the background theory which required during the course in the previous study related to Autonomous Underwater Vehicle (AUV). The first section deals with theories and principles for design any types underwater vehicle. Next, it discussed mechanical design for underwater vehicles and also basic electronic information based on researchers' findings.

In early 1957, Stan Murphy, Bob Francois success to develop the first AUV and later on, Terry Ewart continued the project at the University of Washington. AUV development began in the 1960s at the University of Washington and made very large leaps in the early 1990s with the backing of Massachusetts Institute of Technology (MIT) and the Office of Naval Research (ONR). Next, more and more submersibles are designed and fabricated for different function as shown in Figure 2.1 [1, 2].

Figure 2.1: MIT Odyssey IV [2]

Generally, a submersible vehicle is no more a new impression. The first American submarine was called "Turtle" which built at Saybrook, in 1775 by David Bushnell and his brother, Ezra. In November of 1879, the Reverend George W. Garrett developed the first practical powered submarine, "Resurgam". It was powered by a Lamm 'fireless' steam engine, and could travel for some ten hours of power stored in an insulated tank.

2.2 Theories and Principle Apply

There are several theories and principles are required to discuss during AUV design processes like density, gravity and buoyancy, stability, pressure, hydrodynamic damping and added mass. The vehicle's ability to submerge is influence by buoyancy and density.

2.2.1 Density

Density is defined as the mass of an object per its volume. Mass is the quantity of matter confined in an object (kilograms, Kg) whereas Volume is the quantity of space taken up by a quantity of matter (cubic meters, m^3). Commonly, density can be used to define or determine the substance. This is important in determining how different materials interact when mixed together for AUV mechanical design as shown in Figure 2.2.

Figure 2.2: Density Test [8]

2.2.2 Buoyancy and Gravity (Archimedes principle)

Greek philosopher Archimedes discovered the Archimedes Principle, which proves the object absolutely or partially immersed in a liquid will exist by a buoyancy force which same as the weight of the water it dislocates. In other word, an AUV is submerged into underwater either fully or partially, there exists upward force on AUV that is same as the weight of the underwater that is displaced by the AUV [7].

Basically, the object will sink if the buoyant force is less than its weight and vice versa. When the force is equal to the object's weight will cause the neutral buoyancy to occur and it will stop over immersed in the fluid at that placed as shown in Figure 2.3.

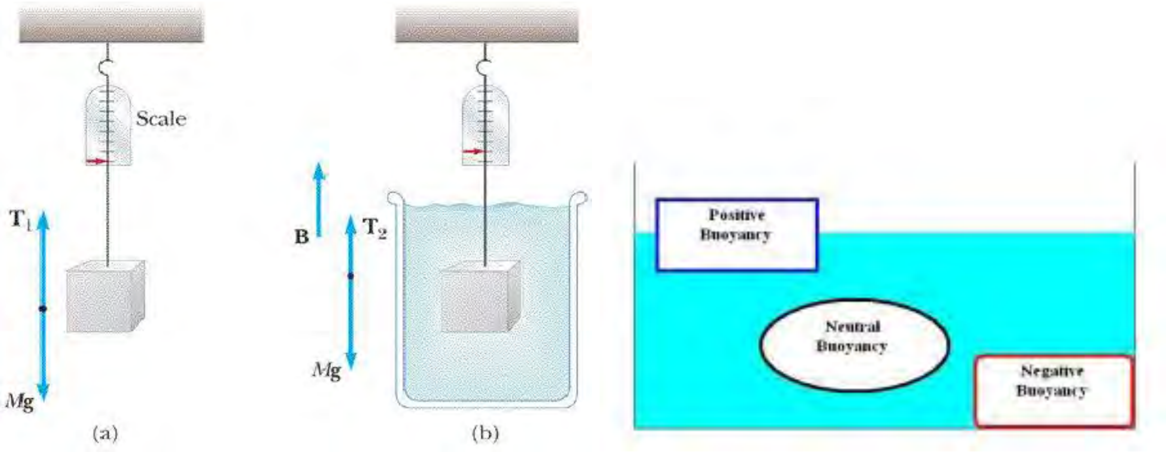


Figure 2.3: The three buoyancy concepts [7]

The ballast tank is filled with air when it is on the water surface cause the submarine's density smaller than that the surrounding water. The ballast tank is flooded with water when it submerges because the air in the ballast tanks is forced out from the submarine until its density is larger than the surrounding water and the submarine start to submerge with negative buoyancy.

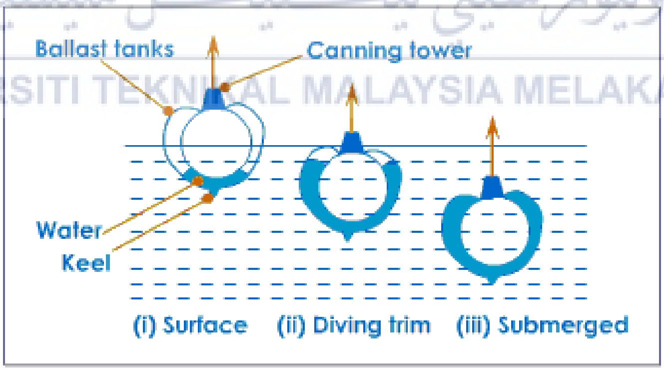


Figure 2.4: The operation of ballast tank [8]

In order to maintain the depth, the amount of air and water in the tanks must be the same, so that its overall density is equal to the surrounding water as shown Figure 2.4. A fish adapt buoyancy by an internal swim bladder same as the AUV, the tank is filled with air to changing buoyancy. The AUV will float when the air flows from the air flasks into the ballast tanks to force out the water until its overall density is smaller than the surrounding water.

2.2.3 Stability Principle

AUV stability is defined as marine architecture area and frame design which contrasts with the method of it behaves at sea either intact or damaged. Stability calculations related to the center of gravity, center of buoyancy and metacenter of pitchers. First, assume that there are no water flows, the centers of mass and buoyancy affected the stability of a static body underwater [7].

For a dynamic underwater body, to increase dynamic stability, the Center of Mass should be associated as the centers of the forces. A floating object is considered stable if it's able to restore itself to a balanced position after a small displacement. As the floating object has upright stability and if the object is pushed down slightly, it produces more buoyancy force. Then, it will push that object back up due to unbalanced against the weight force as shown Figure 2.5.

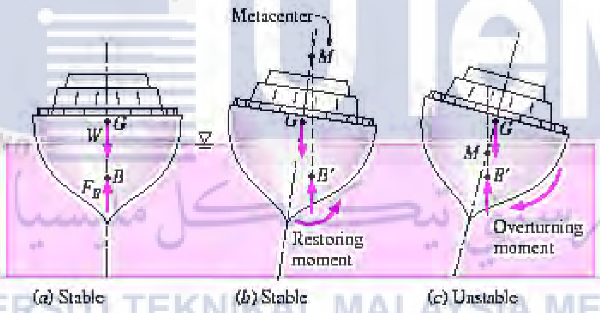


Figure 2.5: Stability of Immersed object [7]

2.2.4 Hydrostatic Pressure

Air pressure is defined as the constant push of air. Daniel Bernoulli, a Swiss mathematician discovered that when flowing air or water speed increased, the pressure will decrease. Hydrostatic pressure is the pressure that is exerted by a fluid at equilibrium with a given point within the fluid, due to the force of gravity. The denser the fluid above it, the more pressure exerts on the object that is submerged. Based on theory, pressure in air is about 14.7 psi or 1 atmospheric pressure at the sea level. Water pressure increases 1 atmospheric pressure for every increase of 10m depth. [6].

AUV depth submerge can determine by the pressure value and this formula. According to Pascal's law, the consequential hydrostatic pressure is isotropic and acts in all directions equally [8, 9]. Pascal law states that

$$(p = \rho g h), \tag{2.1}$$

Where p = water pressure

ρ = water density

g = gravity force

h = water depth

2.2.5 Environment Forces

Environmental disturbances such as natural waves and wind blows on the sea surface influence the AUV stability and motion. Next, unstable temperature or risky sunlight causes the AUV electronic parts to be spoilt. Unstable temperature able causing water in the hermetically closed inside of the AUV and mostly spoilt the electronic devices.

2.3 AUV Coordination System

Generally, an underwater vehicle similar to flying vehicles that have 6 Degree of Freedom (DOF) which include X, Y and Z directions and roll, ϕ; pitch, θ; and yaw, ψ angles. The X-axis moves along the forward direction and is longitudinal translation. The Y-axis point move the right hand side direction and is lateral translation. For the Z-axis is a move along the vertical translation or depth. Thus, in order to keep the vehicle stable when designing AUV, it must be considered the number each DOF [10]. During modelling AUV, it should contract one frame to another reference frame. Figure 2.6 shows the world reference frame represents the first frame to trail the AUV position, orientation and motion. AUV reference frame {B} is the body frame that is a local frame attached to the AUV. The frame {B} moves relative to frame {W} along with the AUV.

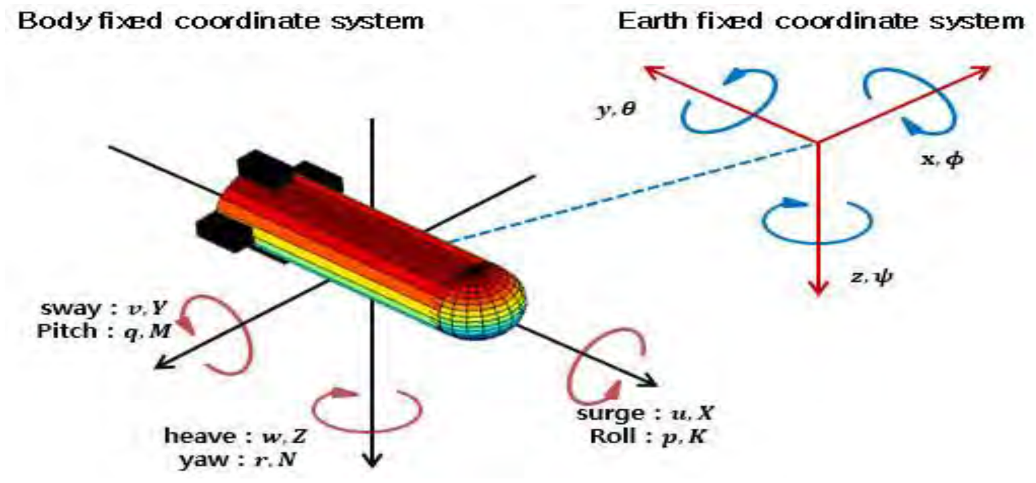


Figure 2.6: AUV coordinate system [10]

2.4 Mechanical Design

The mechanical subsystem consists of the AUV frame, hull, electronics enclosure box, and the propulsion. At this stage, the dimension configuration, mass and weight, material selection, electronic device installation and others required to be considered due to boosting power consumption.

2.4.1 AUV Design Comparison Architecture Frame

There are two common designs for AUV, which are open frame and close frame. Generally, closed frame AUV for uninterrupted fluid flow to the vehicle when at high speed, minimal drag, whereas open frame for allowing fluid flow through the frame due to the large amount of internal mounted thrusters. The following part shows about these two types of AUV include open frame (UTeM ROV, USM AUV, Robbe 131, CUAUV and RAUVI) and close frame (UTeM AUV, Bluefin AUV, Tri-Ton 2, Mako, ODIN and Urasihma).

Table 2.1: Comparison table Architecture design of Open Frame AUV

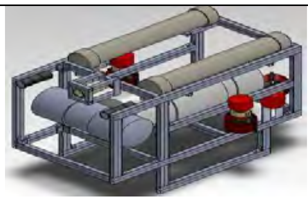
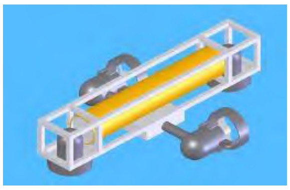
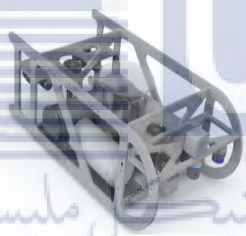
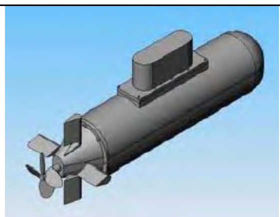
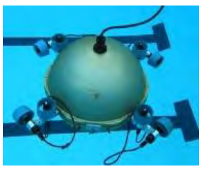
Name	Manufacturer	Architecture	Description
UTeM Smart ROV 1 [11]	UTeM		- 300mm X 600mm X 450mm - 4 thrusters (vertical & horizontal motion with 45◦) - Aluminium frame with vision system & ballast tank - cylinder PVC pipe pressure hull - depth sensor & IMU
USM AUV [12]	USM		- 1m long, 0.5m wide, 30 kg - sensor fusion & actuator control - 2 thruster motors (horizontal) - 2 thruster motors (vertical) - Depth & Gyro sensors - Full state feedback controller
Robbe 131 [13]	Team TomKyle		- Frame is made of polyethylene - 5 BTD150 thrusters - Main pressure hull with a base part polyoxymethylene - Top pressure hull is transparent pipe acrylic glass - All cables are lead to main electronics utilizing cable glands - 4 LiPo Ion batteries packs - Sonar sensor, IDS UI-1241LE-C-HQ camera, Keller 33x pressure sensor, PCB sensor
CU-AUV Ragnarok [14]	Cornell University		- 39 In X 22 In X 21In, 80 pounds - Aerospace frame design - Single hull with camera - 6 thrusters, 5 DOF, 0.6 m/s - Pneumatic actuator system - Visual, acoustic, IMU and pressure sensors - 2 thunder power Li polymer batteries
RAU VI [15]	Spanish Ministry of Science and Innovation		- Acoustic sight sensors and furnished with a robotic arm - 5 DOF hydraulic manipulator - Visual navigation system - 6 different virtual cameras - Holonomic thruster's

Table 2.2: Comparison table Architecture design of Close Frame AUV

Name	Manufacturer	Architecture	Description
UTeM AUV [16]	UTeM		- skeletal frame is made from aluminium - 2 cylindrical hulls - 4 motors fin propeller & wing - Tank with float lever switch - DC and Servo motor
Bluefin [17]	Bluefin Robotics Corporation		- length of the 12" and 21" - Tailcone ducted thrusters - IMU, GPS, depth sensor
Tri-TON 2 [18]	University Tokyo		- 1.4m X 1.5m X 0.8m, 260 kg - 3 pressure hulls - 5 thrusters (4 directions) - Maximum speed 0.6 m/s - Maximum depth 2km - 4 Li-Ion 26 V 30 Ah - Sensor DPT6000 depth sensor
Mako [19]	University of Western Australia		- 1.4m X 0.6m X 0.5m - 2 hull, 4 thrusters - a ballast tank - 2 vertical thrusters - Depth 2100 echo sounder, digital magnetic compass, sonar
URAS HIMA [20]	Mitsubishi Heavy Industries		- 10m X 1m X 1m, 10 tons - Maximum submerge depth 3.5km - Cruising range 300km - PEFC fuel cell or Li-ion re-chargeable battery - side scan sonar, video camera, sub-bottom profiler, multi-beam echo sounder - Oil bladder for buoyancy
ODIN [21]	Autonomous System Lab		- 0.64 m diameter sphere made of aluminium AL6061 - 123.8 kg & 1.3N positive buoyant & 100 m depth rated - 8 Tecnadyne brushless thrusters via four fabricated mounts, Pressure.

2.4.2 AUV Frame Design

There are two common designs for AUV drawings which are open frame and close frame as shown in Figure 2.7. Vehicles with high aspect ratio used for long moving distances and vice versa. There are advantages and limitation for each type of design. However, the shape of the vehicle is just depends on the purpose and application for it.

If the vehicle operates at low speeds (maximum speed, approximate 0.5m/sec), then closed frame design is no more suitable for it because it does not offer a major benefit than an open frame design. However, an open frame design is simple, quick availability by monitoring any peripheral on the AUV. Open frame design will exhibit high symmetry, modularity and stability compare to the close frame design.

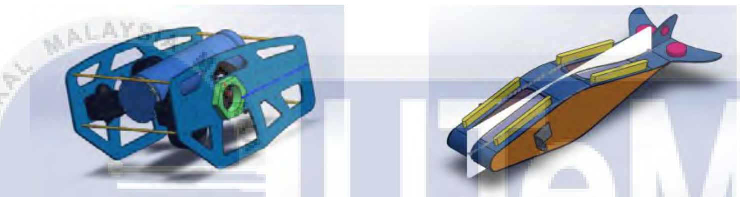


Figure 2.7: Isometric view for open frame (Left) and close frame (Right) AUVs

Based on an AUV design report which proposed by Team 5374 from the University of Arizona (Figure 2.8), they used several sheets of 6061 Aluminium sheet and engrossed them in firm and light frame. The main frame has two downhill curves to mounting two cross upkeep dishes. A skid plate along the frame and two supporting plates act as dose the core microchip technology casing in the home. Due to the open frame design, bigger segment is cut out to increase water flow about it when it moves. When it moves in underwater, the water will flow faster through the cutter segment as similar to the Bernoulli Principle.

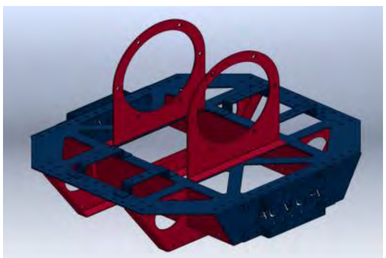


Figure 2.8: Open Frame design by Team 5374 from University of Arizona [10]

2.4.3 AUV Hull Design

Pressure vessel hull must provide for keeping its components in a dry and waterproof situation when design an AUV. This hull is important to permit devices simply available and sustainable for future changes or additions component. Some AUV design might have more and more small hull or the enclosure box (discuss in the next section) inside the main hull. There are various shapes that able to design such as spherical hulls offer the best structural integrity, but limited space for components while rectangular shape gives the efficient use of the space available for most components whereas cylindrical shape provide more physical and space for keeping more electronic elements.

The hull must be light and strong, high durability and corrosion resistant as it will be submerged into a saltwater environment as Figure 2.9. First, Polyvinyl Chloride (PVC) is the best match for those criteria. The principal goal of AUV design effort is to fabricate a vehicle that is small, low cost, easy to deploy and others. PVC is a widely used thermoplastic polymer.

Based on CUAUV Ragnarok [14], they proposed non-metal pressure vessel designed to maintain signal reliability and mounted near the top of the vehicle. It comprises the MicroStrain 3DM-GX1 IMU and passes its signal to the main hull via a SEACON connector. The connectors display board cast in clear epoxy which indicates remaining charge.

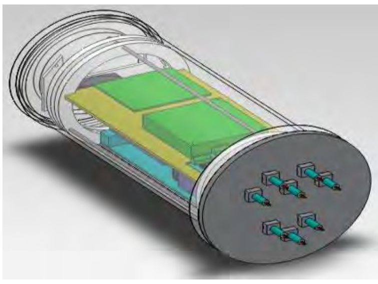


Figure 2.9: AUV cylindrical pressure hull [14]

First, it needs to maximize the volume while at the same time minimizes costs. Next, it maximizes the AUV strength to reduce failure in high underwater pressure. Last, diminishes the drag force to increase velocity because more velocity causes less time taken, fewer properties intake like petrol fuel and air and energy used.

2.4.4 AUV Electronic Enclosure Box

The concept of the electronic enclosure box is similar to hull concept just the size is smaller than the hull. All AUVs are functionally by the use of electronic component, but cannot be open to underwater due to short-circuit and easy spoilt by high underwater pressure. Thus, hard enclosure box is needed for them to function well in underwater areas. Figure 2.10 shows the design of the waterproof box. The cover of the box needs to be transparent because simply to detect the function inside it. Normally, cylindrical shape or spherical shape more proper in design the shape of the enclosure box. It will be put in the pressure hull. The underwater pressure rise rendering to its depth, thus the box should be thick dependent on depth. Thus, light and robust structure material for it is important.

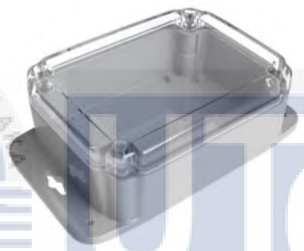


Figure 2.10: Electronic waterproof housing box [11]

Based on the freshman project, which organize by Polytechnic University, they have chosen Pelican 1010 case as the RCX's water-proof housing as shown in Figure 2.11. There are six small hovels bored in the case which are three holes for the input wires and three of the output wires. The wires were then inserted into the appropriate holes. Marine GOOP was applied to the holes to form a water tight seal around the wires. The wire was then inserted into the case and the connector head re-attached to the wire [22].

Figure 2.11: Pelican 1010 case [22]

2.4.5 Propulsion System

AUV mostly uses motors for propulsion (movement caused by a force) due to the cost of alternative systems. The AUV degrees of freedom are controlled by the location of the motor. The force acting by the thruster can make it move in 6 DOF. The waterproof thruster design can be divided into several parts include DC motor, coupling shaft and propeller as shown in Figure 2.12 [24]. The propeller is defined as a method containing an air foil formed blades straddling about a shaft and spun to generate propulsion system over underwater or air or to cause water flow in a pump [25]. This is done by accelerating the water that enters the propeller. Force (thrust) is defined as the change of rate of momentum. Based on Newton's second law says that force is the product of mass and acceleration. By increasing either acceleration of the water flowing through the propeller or the rate of mass flow, more thrust will be produced.

A propeller is a rotating fan used to propel the AUV by using the power generated and transmitted by the main engine or motor. The transmitted power is converted from rotational motion to generate a thrust which imparts momentum to the water, resulting in a force that acts on the ship and pushes it forward. A pressure difference is created on the forward and side of the blade and water is accelerated behind the blades.

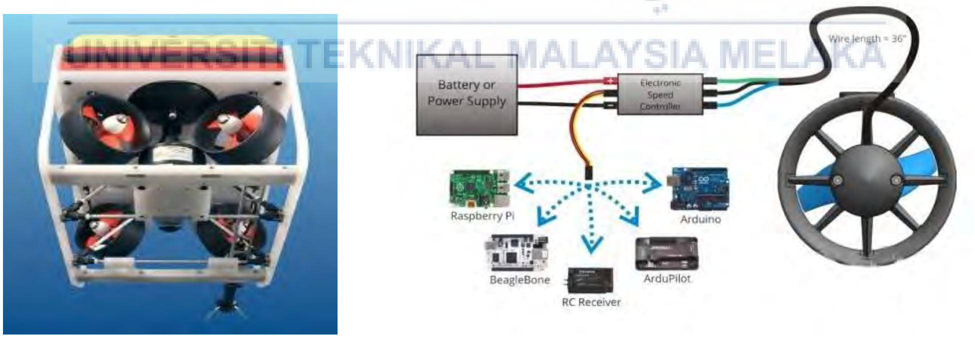


Figure 2.12: Propeller system and Thruster used by AUV [24]

Figure 2.13 shows the Polytechnic University freshman project [23], they have chosen Lego companionable propellers which simply made by implanting a Lego piece covered in plastic wrap into the hole of the propeller. To ensure that the propeller stays on snug and does not fall off, a plastic has wrapped between the propeller and the Lego shaft. Lego DC motors are used on the AUVs to provide motion and no trouble running in underwater.

Figure 2.13: Lego compatible propellers [23]

BTD150 thruster from SeaBotix is a DC engine which needs constant speed to enable controlled motion of the AUV. A suitable speed controller is important to regulate the engine speed of the thruster. The AUV Team TomKyle used five thrusters; each regulated by the developed speed controller and connected to a common CAN bus [13]. However, CUAUV Ragnarok used 6 brushed motor COTS thrusters. Each of the cores AUV axes is concerned with two thrusters which are VideoRay GTO 3 thrusters (surge), SeaBotix BTD150 thrusters (sway and heave) [14].

2.4.6 Submersion System

For an AUV to submerge and float underwater, either using heavier materials (added mass) through ballast tanks or thrusters (propulsion system). A tank is the easiest method to submerge by only involves taking and removing water. The second method is using thrusters to point downwards which are simple but then consume more power. Since the volume of the AUV keeps constant, the downhill force rise acting upon it to buoyancy force in order to submerge deeper.

Based on the Urashima AUV [20], a better submergence performance is the precise vehicle balance adjustment between weight and buoyancy cannot be attained just by dropping ballast weight. Buoyancy changes caused by water density changes and shrinkage of the vehicle body caused by increased water pressure and drops in temperature should be considered in balance adjustment. MHI has developed an oil bladder type buoyancy adjusting device that can perform such adjustments and attain neutral buoyancy of the vehicle.

2.5 Electronic Design

Electrical subsystem is the soul for construction which giving energy power to its part included propulsion system, sensors and the controller to function well. First, the power supply is described and many sensors used to certify mechanical failures that are not affected in any electronic issues.

2.5.1 Electric Power Supply

The power supply in underwater plays important role in moving it mainly AUV in a period since there is no power source station in area underwater or ocean. Besides that, the power source should be a small size and not heavy that can insert in a hull or enclosure box. The ideal arrangement of batteries is in parallel between each other to avoid current flow between them. Saving power electrical components should be to save the battery power and provide more energy for a long period.

Based on USM-AUV, they proposed to use a pack battery that covers four 12 Volt batteries to supplying entire electronic component. Two pair of batteries are supplying for thrusters and propeller whereas another two pair of batteries supplying for electronic components like sensor. They used on-board power to enable the AUV function in autonomous mode [12].

Tadahiro Hyakudome [26] proposed that lithium ion battery is a good choice for every component in AUV due to surrounding high underwater pressure low temperature situation are not suitable for those chemical reactions in underwater area. Some oil is used together with the battery for equating the surrounding pressure and insulated in underwater areas.

AUV Robbe 131 designed by Team TomKyle (2014) [13] proposed that AUV is powered by two battery packs consists of 24 single lithium polymer (LiPo) batteries in a 6S4P circuit with a charge of 10:4 Ah at a nominal voltage of 22:2V. They proposed a battery protection by an internal protection circuit which limits the current to 20A.

Two thunder power lithium polymer batteries used to run Ragnarok [14] with about 1.5 hours. Lithium polymer batteries are hot-swappable and thus AUV can be kept running during the batteries are changed. To prevent batteries over discharge, custom circuit boards in the battery pods monitor the battery charge and shut off the packs. Then, all incoming power to the vehicle is routed through the merge board to provide a single power rail for the vehicle.

2.5.2 Sensors

First sensor used by AUV is the depth sensor. By gauging the external underwater pressure, the depth value can be easily determined. The depth for AUV submerge is important because if submerge too depth may affect water leakage and spoilt the AUV system. REMUS proposed analogue strain gage sensor as the pressure sensor for each sample of control round software. AUV base frame 14 bars (200 psi) gage with a depth tenacity of about 0.03m.

The ORCA 1 equipped with few navigation sensors that the pressure sensor (PX202-015AV) to measure underwater vehicles depth. The gyroscope (MG100) acts as the measured position of underwater vehicle. The accelerometer (ADXL50) used to measure underwater vehicle acceleration. The compass (TCM2-20) measures underwater vehicle heading [2].

Based on Project Mako [19], they used 200 kHz frequency depth voice transducer sonar system to determine AUV depth. A Navman Depth 2100 echo sounders is offering a basic but real depth sensor. It is placing downhill on the AUV to allow feedback only if underwater depth is identified. Figure 2.14 shows the AUV depth value is easily separated by the difference between the depth of the underwater and echo sounder value.

Figure 2.14: The Pressure sensor as depth sensor [19]

Based on Urashima AUV [20], a multi beam echo sounder used to determine the depth and surrounding in the underwater area. The operation is spread audio pulses vertical in the touching direction generate underwater scene. As it spreads sound and accepts echoes, a high-resolution image generates when the AUV is travelling near the bottom in deep water.

Next, Sonar sensor has the similar function to Ultrasonic sensor, just difference use of land and water. Sonar sensor gives a relatively large frequency pulse and multiply the time taken it take for the echo to reflect back. Third sensor used is a water detector sensor. Any discoveries of water will directly close performance and activate alternative seeming. An Inertial Measurement Unit (IMU) is used to give acceleration forces, gyroscopic forces and a compass heading. Navigation purpose and position AUV submersible usually using this IMU.

2.6 Software (SolidWorks, Arduino, MATLAB)

Generally, SolidWorks software is widely used in engineering design to reduce financial prototypes, redraft and saving period consume. Before AUV fabrication, the analysis tools could provide an overview of how the designs would perform in real environment. The designer would alter the design so that it can perform better before fabricate it. It is able to perform different type of analysis on the design that has been draw included structural, fatigue, motion, sustainable, thermal, vibration, fluid flow and others. Its featured capabilities analysis included linear stress, finite element, metal fatigue, nonlinear, thermal structural, frequency and others. The user is able to choose any type of materials and undergo the analysis.

Arduino Mega 2560 is a microcontroller board based on the ATmega2560. It suits to use due to contains everything to support the microcontroller as simply connect it to a computer with a USB cable or power it with an AC-to-DC adapter or battery to get started. Arduino used to receive the data signal from the sensor and then process and send back the signal to actuator. For example, depth sensor read the actual underwater pressure and sends to Arduino to process, thus the thrusters will move forward or backward direction as the coding set by user [5].

MATLAB is optimized for solving engineering and scientific problems. There are a lot of libraries rebuilt toolboxes with algorithms essential for many applications, especially real time applications and interface with the Arduino. The movement control of AUV can be done by using the toolbox in MATLAB include PID, FLC and Neural Network [22]. For Proportional Integral Derivative (PID), proportional controller (kp) reduces the rise time and steady state error while the integral controller (ki) eliminates the steady-state error for a constant or step input but the derivative controller (kd) increases the stability of the system as shown in Table 2.3. Fuzzy Logic Controller (FLC) designed to emulate human deductive thinking and decision making from what they know. FLC has been primarily applied to the control of processes through fuzzy linguistic descriptions. FLCs are reasonably easy to design, but the tuning process of FLCs through trial-and-error approach will continue until satisfactory results are obtained. If the results are not as desired, changes are made either to the number of the fuzzy partitions or the mapping of the membership function and then the system can be tested again.

Table 2.3: Effect of increasing *Kp, Ki* and *Kd* parameter [5]

Parameter	kp	ki	kd
Rise time (s)	Increase	Increase	Decrease
Settling time (s)	Small Change	Increase	Decrease
Overshoot (%)	Decrease	Decrease	Small Change
Steady State Error	Decrease	Remove	Small Change

2.7 Summary

As a conclusion, it introduces a summary completed the whole mechanical, electronics and sensor design part. It also discussed some history of AUV, hardware, mechanical and electrical system of AUV Basic idea to develop and modelling of AUV optimized after doing research on previous subtopics. Previous AUV design and development are useful for further research in AUV field.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discusses the organization of this project. Basically, it will describe and explain the procedure or technique to achieve the research goals of the project. It gives the general idea to the reader from the initial stage to the final stage. From an introduction and background of the project until the project design, this chapter will provide step by step guide to the reader so that they can understand the project well.

Firstly, overall project flowchart is included in this chapter as shown in Figure 3.1. It explained briefly how the project starts until the end. After that, a more specific flow chart regarding the methodology flow of this chapter is provided as shown in Figure 3.2. This flowchart gave an overall view about what is going to be discussed in this chapter.

Next, some of the important hardware in mechanical parts used is being drawn and provided with a diagram. Moreover, the type and method of analysis done in SolidWorks software is discussed. Lastly, the experiment implementation procedure of the project is listed out with step by step with pictures of the experiment setup.

3.2 Project Flowchart

The project flow chart listed out the overall process that has been taken to complete the project. Figure 3.1 shows a rough idea about the flow of the project from planning, gather information until fabrication and experimental test. The steps taken are further explained in the next section.

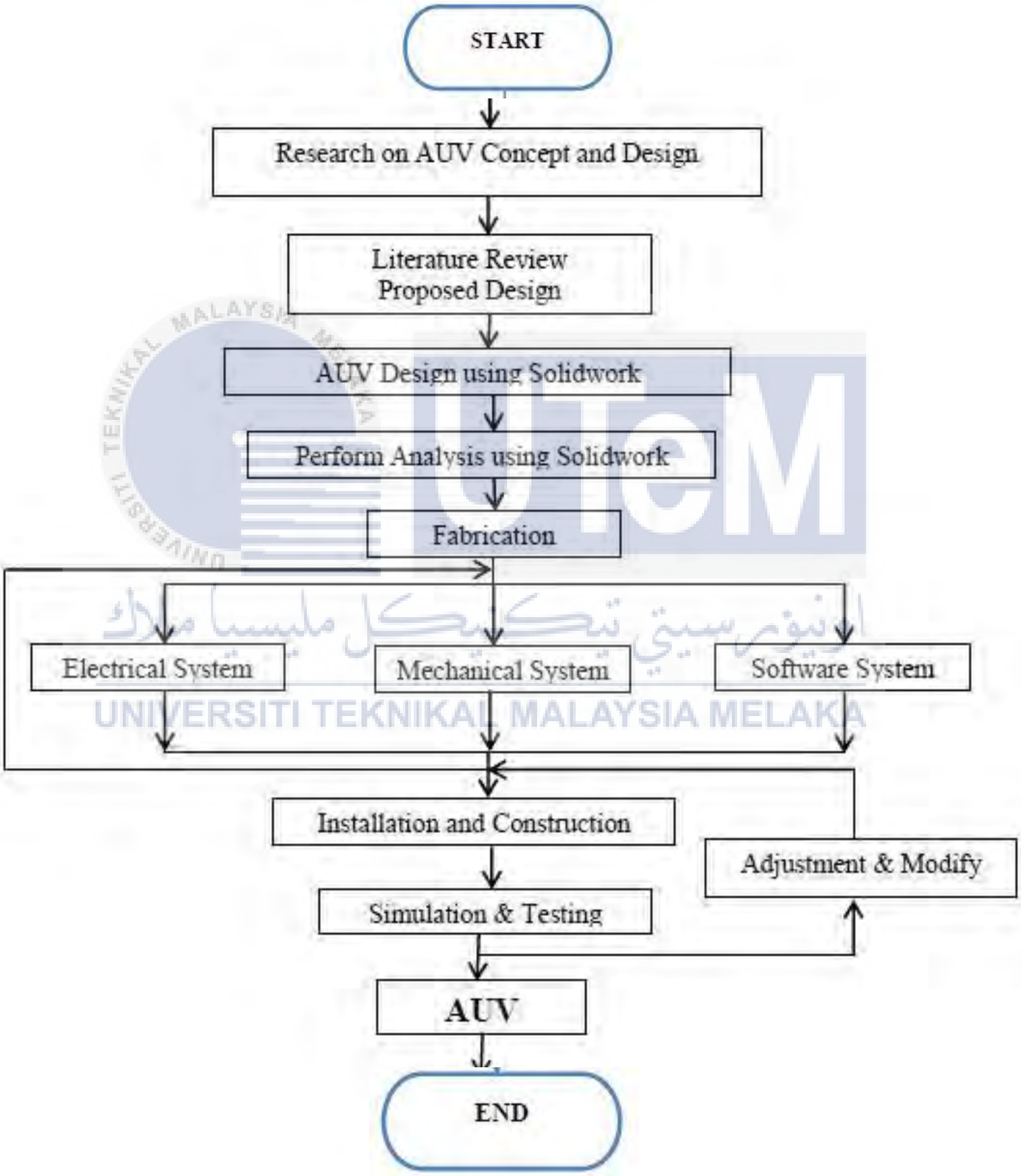


Figure 3.1: AUV project flowchart

3.3 Project Methodology Flow Chart

The AUV project methodology flowchart of this project is shown in Figure 3.2. The flowchart gave an overview of the contents that are included in this chapter. This chapter discussed the method used to complete this hardware and software design AUV project.

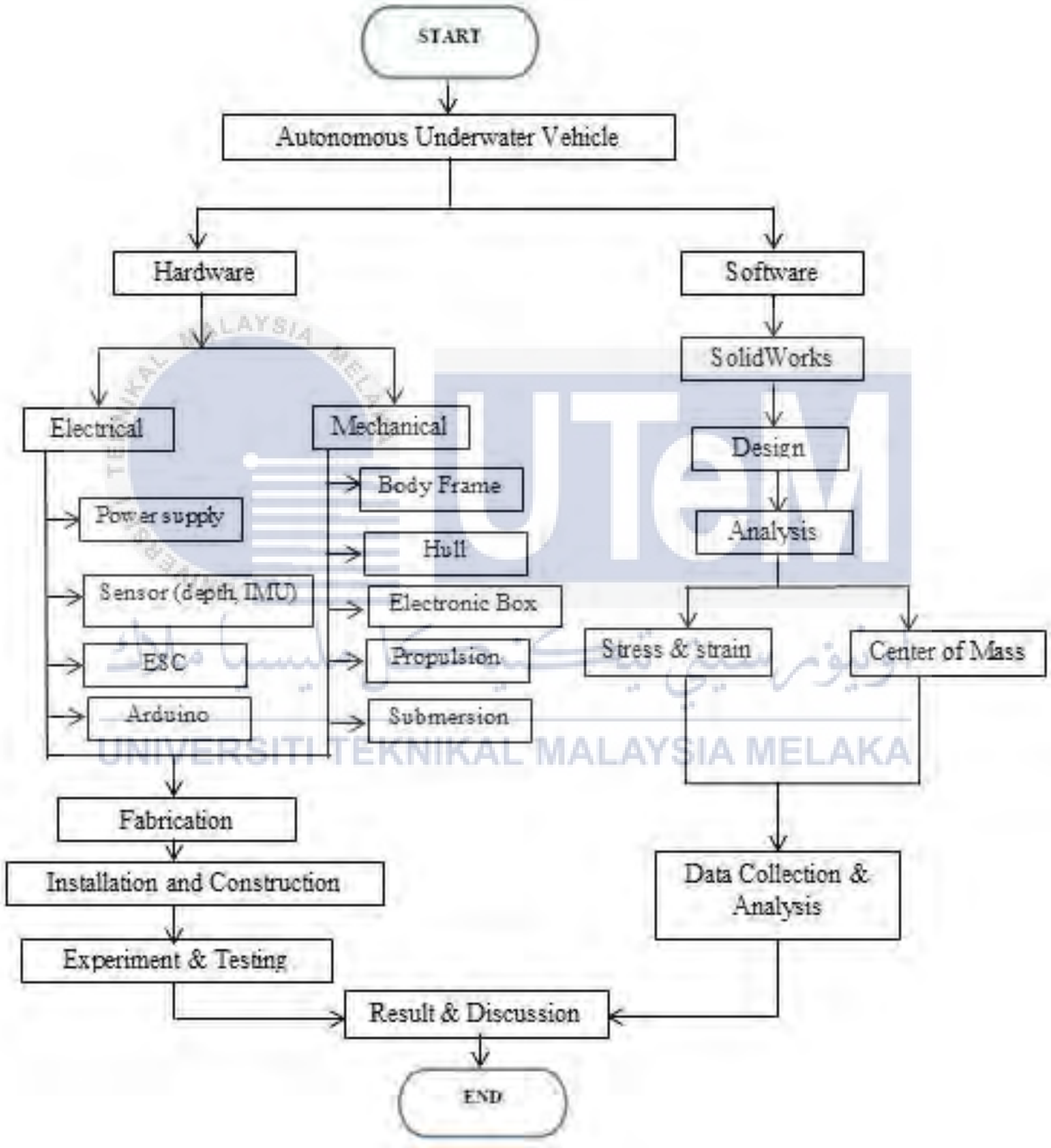


Figure 3.2: AUV project methodology flowchart

3.4 Project K-Chart

The project k-chart of this project is shown in Figure 3.3. The k-chart gave a tool for systematically organizing research in this chapter.

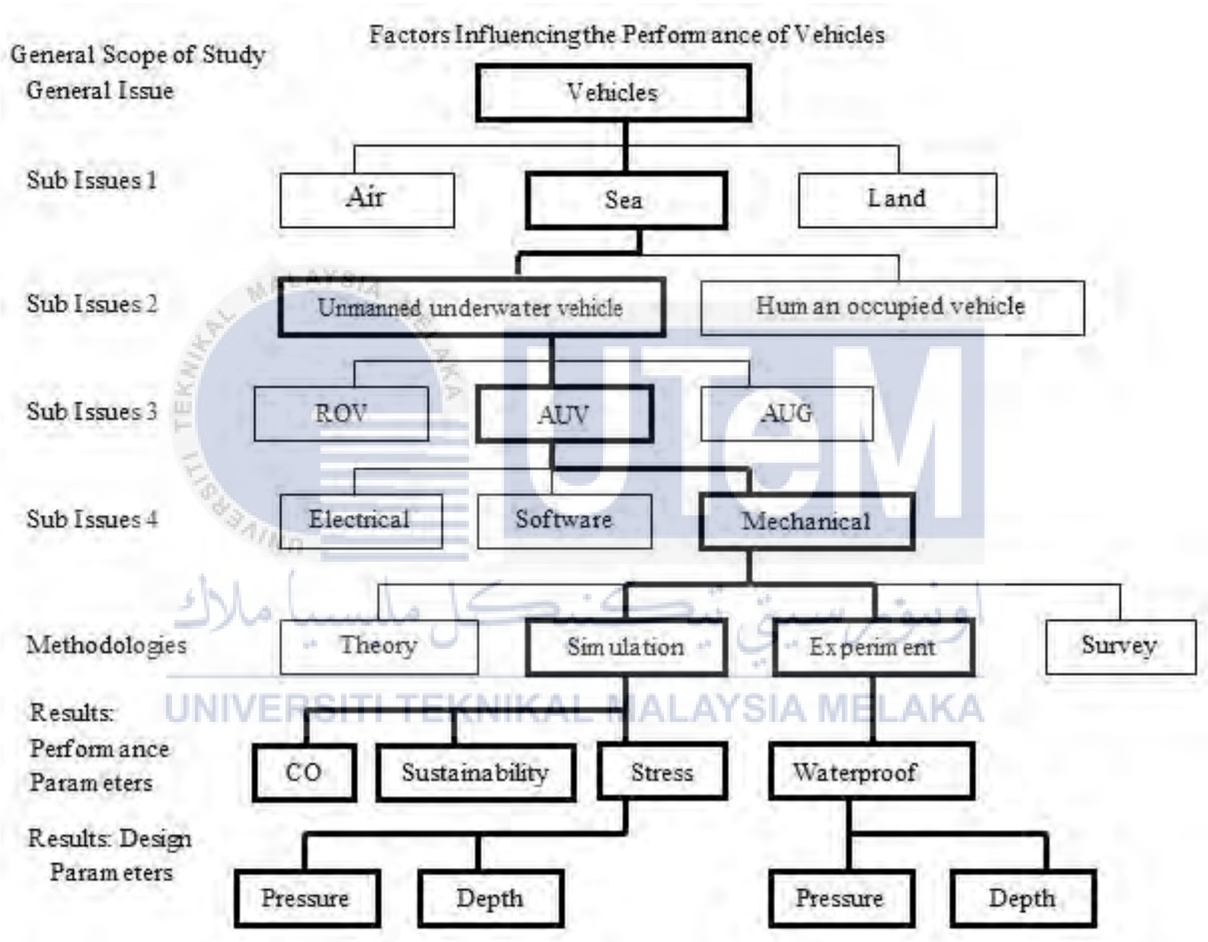


Figure 3.3: K-Chart

3.5 Mechanical Description (SolidWorks Design)

3.5.1 AUV Body Frame

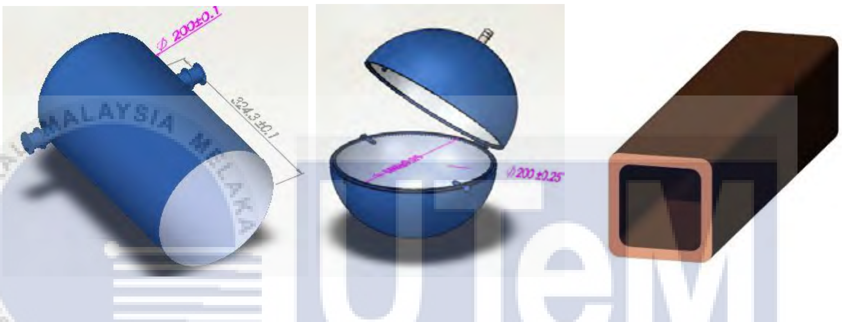
Basically, the frame is the important part because it supports whole AUV assembly parts. The final decision made is to design an open frame AUV due to some reasons. First, open frame is more flexible in terms of shape because its shape can be change or edit easily rather than close frame. Normally, close frame is designed as a submarine, fish or marine animal shape while open frame more likely ROV shape. Close frame has limited shape of the pressure hull since all the boxes or component can only keep inside the frame.

The acrylic frame is fabricated in Underwater Technology Research Lab after doing the design. Figure 3.4 shows the AUV frame design using Acrylic due to its light weight specification and struggle erosion from the sea water and chemical materials. Four skid rods are used in between the frames for improving stiffness. This structure of the frame support the hull and four thrusters yet permits additional adding components. It is easier to change the shape, access and removal or substitute additional components in the future.

Figure 3.4: AUV open body frame (Design & Fabricated & Structured)

3.5.2 Pressure Vessel Hull

The pressure vessel hull keeps all electronic elements premeditated easy disassembly. AUV ODIN uses spherical hull shape while Project Mako, Robbe 131, USM AUV uses cylindrical hull shape whereas UTeM AUV using rectangular hull shape. For a cylindrical shape, a 140mm outer diameter and 126mm inner diameter by 7mm thick and 343mm long is being drawn in Solid work as shown in Figure 3.5(a). The spherical shape is drawn with a 200mm outer diameter and 188mm inter diameter as shown in Figure 3.5(b) while rectangular shape is drawn with size of 100mmX140mmX340mm as shown in Figure 3.5(c).



(a) (b) (c)

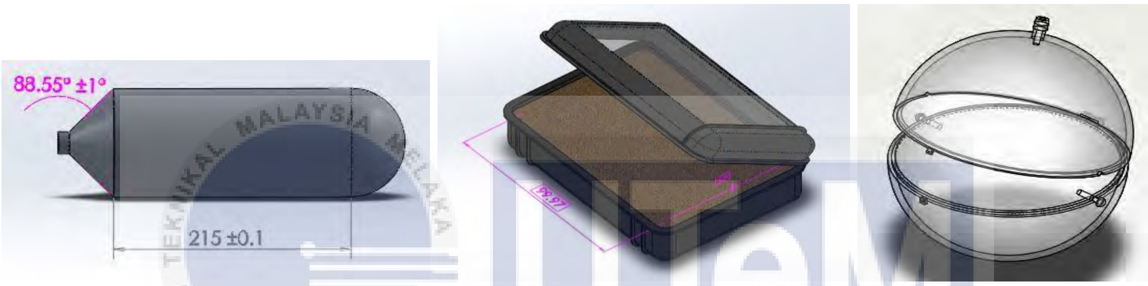
Figure 3.5: Three types of AUV hull shape

Figure 3.6 shows the PVC pipe cylindrical hull shape with 154mm outer diameter and 150mm inner diameter with 4mm thick and 550mm long made by polymerization of the Vinyl Chloride Monomer (VCM) is chosen for the final hull shape. Two PVC end caps are pushed onto either end of the tube by silicone sealant and PTFE white Teflon thread sealant tape. One another as one end cap fixed to AUV frame and hull to allow wires in and out for carrying energy to and from exterior mechanisms.

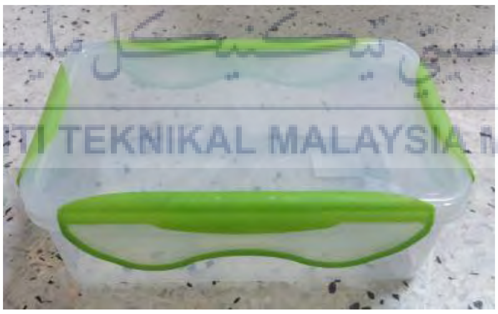
Figure 3.6: Cylindrical hull (Design & PVC pipe)

3.5.3 AUV Electronic Enclosure Box

The concept for the electronic enclosure box is similar to cylindrical hull just much smaller size. The enclosure box reduces the chances of electronics damage in the event of minor water intrusion. There are also a few types of different shape for enclosure box include cylindrical, spherical and cubed. For a cylindrical shape, a 100mm outer diameter and 80mm inter diameter by 10mm thick and 200mm long is being drawn in SolidWorks as shown in Figure 3.7(a). Spherical shape is drawn with a 150mm outer diameter and 130mm inter diameter as shown in Figure 3.7(b) while cuboid shape is drawn with size of 110mmX60mmX50mm shown in Figure 3.7(c).



(a) (b) (c)



(d)

Figure 3.7: Four types of electronic enclosure box shape

A cuboid shape enclosure box measure 200mmX140mmX80mm in Figure 3.7(d) is choosing as it allows sample room for the AUV's control electronics board. It is made of plastic alloy which is strong and light and transparent for clear vision to see through inside the box. It is a superb impact strength, dimensional stability and mechanical performance. After electronics are mounted, the box will be put horizontally in the hull of the AUV.

3.5.4 Propulsion

Propulsion is basically a converter for the action of driving or pushing forward. There are two aspects to be considered when choosing a propeller for AUV, which are propeller pitch and diameter. Propeller blades are varying from 2 blade propeller up to 6 blade propeller and maybe more and more (Table 3.1). But, 3 blades and 4 blade propellers are usually used by the underwater vehicles especially AUV. Propeller pitch is the hypothetical frontward drive for a revolt propeller to translation a propeller creates for every full revolt of

Table 3.1: The comparison for different type of propeller pitch [25]

Fixed Pitch Propeller	Controllable Pitch Propeller
The blade is permanently attached to the hub and the location of the pitch is always static	Rotating the blade to alter the pitch of mechanical and hydraulic arrangement
Strong and consistent since system not unite any mechanical and hydraulic connection	Hydraulic oil in the tank used to regulate the pitch may slip out and cause oil pollution
Costs spending is cheaper than CPP type	Multifaceted and luxurious system

After comparison, the thruster suitable to use is BlueRobotics Thrusters T200 as shown in Figure 3.8 and 3.9 made of aluminium alloy with three blades and a lower pitch. T200 Thruster is a low-cost, high performance thruster for marine robotics. It has a cable containing three wires connected to the three motor wires to the electronic speed controller (ESC). Two horizontal thrusters place beside the hull to gives a surge in both forward and backward directions, whereas others two vertical thrusters place inside the frame to gives the heave in both submersible and float actions. The sway motion can be control of the speed of horizontal thrusters. The thruster structure designs to place in symmetry to maintain AUV stability. Table 3.3 shows the T200 specifications.

Figure 3.8: BlueRobotics Thrusters T200 [25]

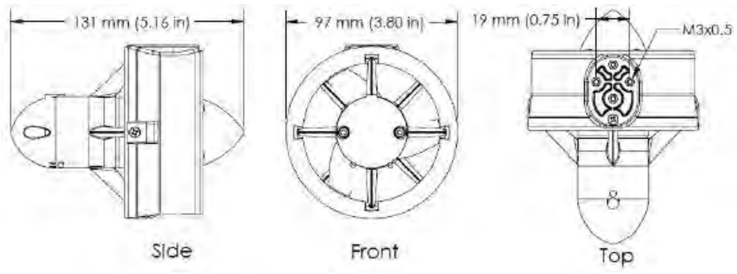


Figure 3.9: Orthogonal View with parameter for T200 Thruster [25]

Table 3.2: Specifications of the thruster [25]

Parameter	Value
Model	BlueRobotics T200 Thruster
Maximum forward/ backward thrust @ 16V	50N / 40 N
Rotational Speed	300.38 rev/min
Operating voltage/ Max current/ Max power	6.2V/ 25A/ 350W
Length/ diameter/ weight (air)	131mm/ 100mm/ 422g
Propeller diameter	76mm

3.5.5 Submersion system

This project adds weight (iron steel) for increase the AUV weight until 80% of body to submerge in water (still positive buoyancy) in order to reduce the power drain by the thruster to move heavily. The iron steels are put inside the small PVC pipe as 62mm outer and 60mm inter diameter with 1mm thick and 550mm long dimension and fixed the position by the foam (Figure 3.10a). Both weights are attached left and right AUV bottom body for stability and balancing (Figure 3.10b).

(3.10a) (3.10b)

Figure 3.10: Submersion system [26]

3.5.6 AUV Prototype Assembly Drawing and Actual Structure

Finally, a complete AUV design is done by combining and assembling all the mechanical parts. UTeM AUV is shown in Figure 3.11 with 70cm length, 50cm width and 30cm height an approximately 5.5kg (from SolidWorks simulation). The shape is fairly symmetrical. It includes a cylindrical pressure hull made of PVC pipe riding an auxiliary PVC open frame structure. Two cuboid shape enclosure boxes are put inside the hull. Two horizontal thrusters mounted beside the hull whiles the others two vertical thrusters mounted beside the frame. In order to increase dynamic stability, the thrusters arrange in a line with COM, regular and easier architecturally frame is being proposed.

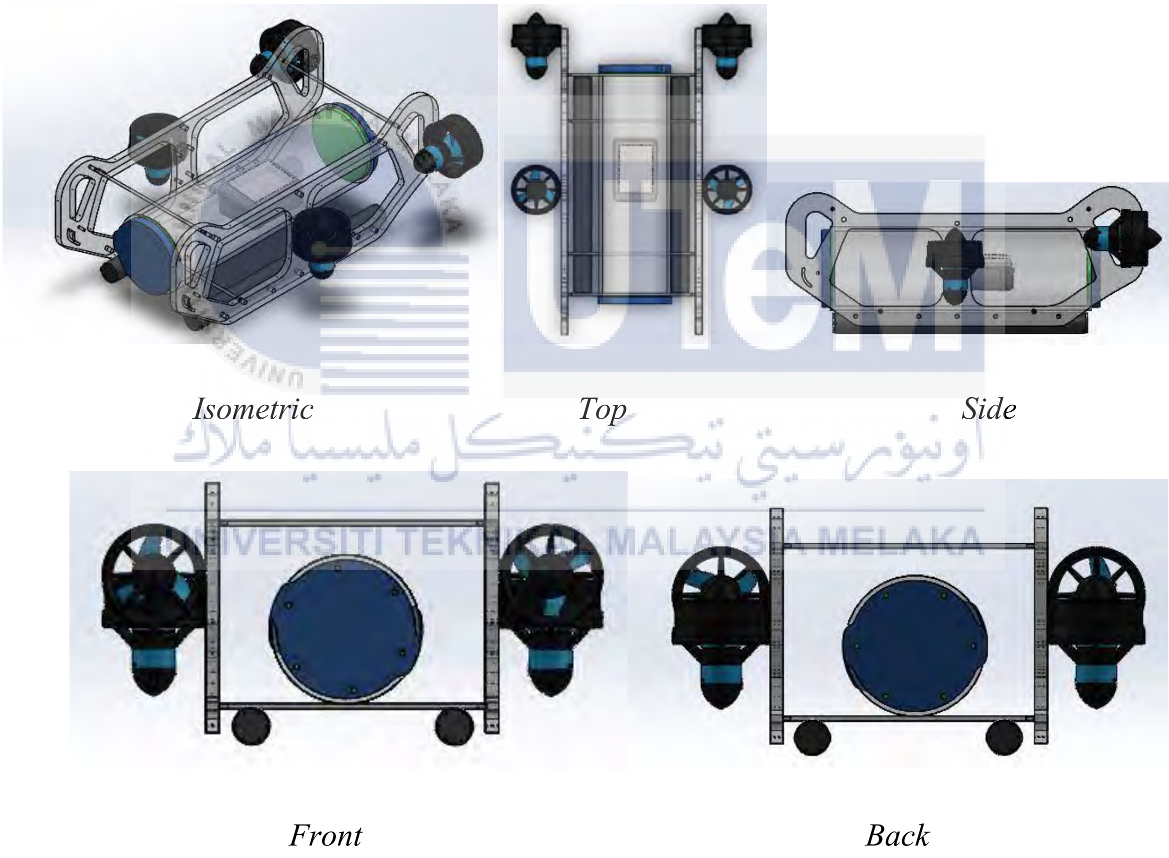


Figure 3.11: AUV assembly drawing

Next, the Figure shows the actual AUV structure after all hardware was fabricated and combined.

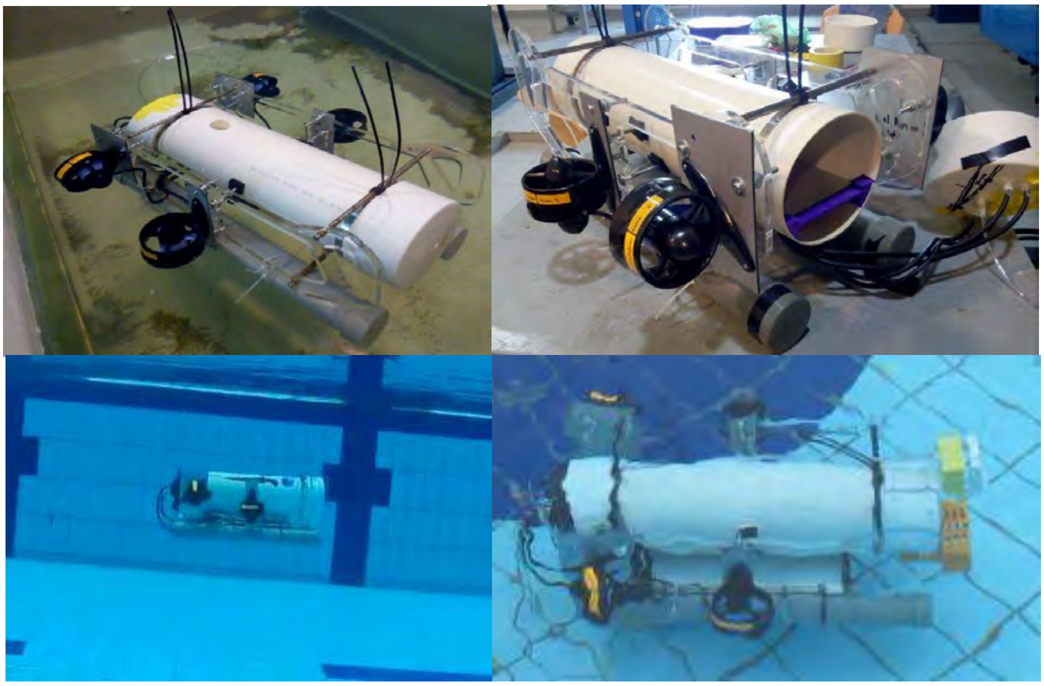


Figure 3.12: AUV Prototype

3.6 Electrical Description

Figure 3.13 and 3.14 shows the AUV is equipped with power supply circuit include Arduino Mega 2560, Depth sensor MPX5700AP, 10 DOF IMU sensor, AfroESC 30A, 9V Energizer battery and 12V Lead-acid battery. Power supply provides 12V direct from battery to ESC for thruters while 9V battery supplies power to Arduino to function. ESC is electronic speed controller for motor propeller thruster. Pressure sensor MPX 5700AP used to measure pressure and AUV travel distance in Z-axis.

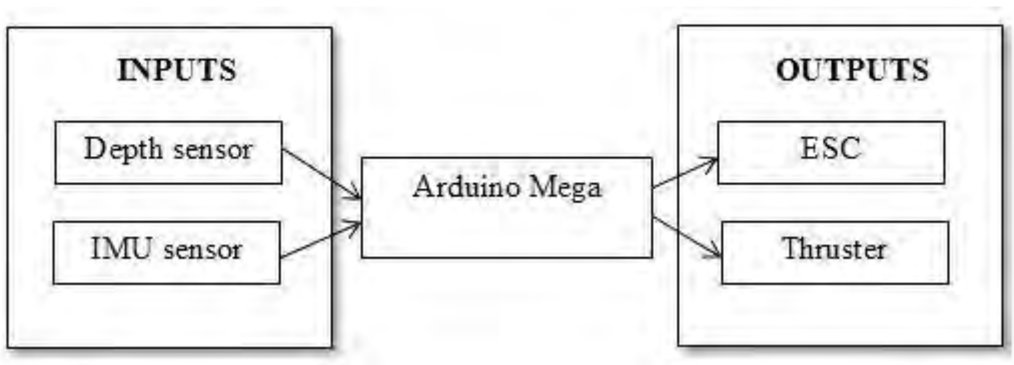


Figure 3.13: Block Diagram of the Embedded System Design

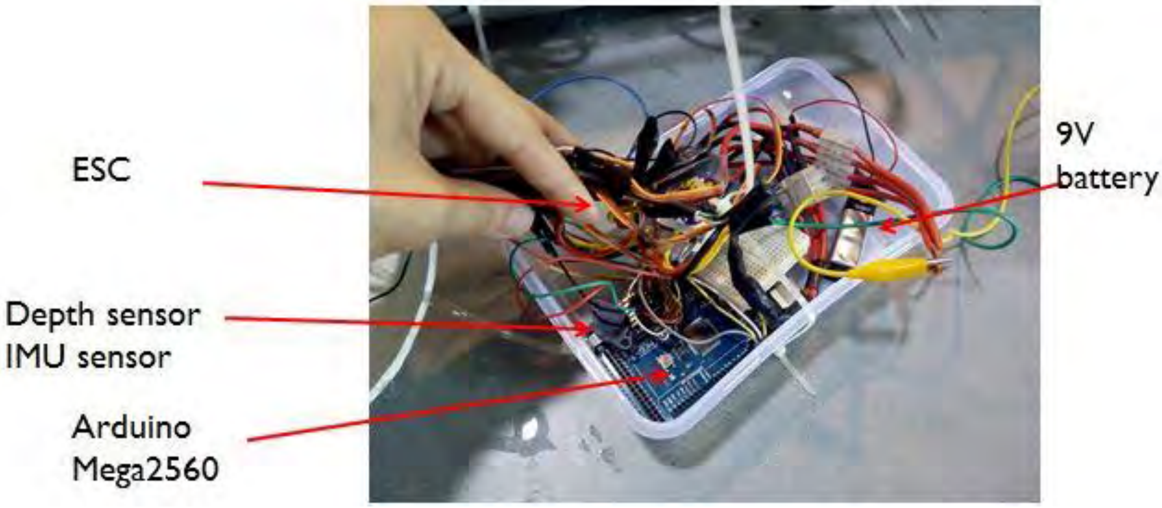


Figure 3.14: Electrical parts

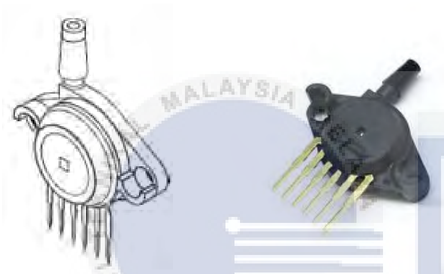
3.6.1 Electric Power Source

Based on the previous AUV project, lithium ion or lithium polymer is the best solution for power supply. However, due to budget issues, lead-acid battery will be used instead of lithium ion battery. Figure 3.15 shows the 12V 7.2Ah lead-acid battery used to supply the ESC to thruster since it required 6V-16.8V to work. Also, 9V energizer battery used to power up the Arduino since Arduino required only 7V-12V to work and it placed inside a Tupperware due to easily take out of the PVC hull.

Figure 3.15: 12V Lead-acid battery (Left) and 9V Energizer battery (Right)

3.6.2 Depth Sensor

The pressure sensor is linked thru the pressure hull of the outside AUV. The pressure position detecting location is struggling to confusion causes of AUV movement. MPX5700AP is chosen for determining the depth of AUV submersion. The MPX5700 series piezoresistive transducer is a state-of-the-art monolithic silicon pressure sensor designed for a wide range of applications and employing a microcontroller with A/D inputs as shown in Figure 3.16. It has a pressure range from 15KPa to 700KPa; supply voltage range from 4.75VDC to 5.25VDC; sensitivity of 6.4mV/KPa; maximum depth up to 70 meter.



UNIBODY PACKAGE PIN NUMBERS			
1	$V_{OUT}^{(1)}$	4	N/C(2)
2	GND	5	N/C(2)
3	V_S	6	N/C(2)

1. Pin 1 in noted by the notch in the lead.
2. Pins 4, 5, and 6 are internal device connections. Do not connect to external circuitry or ground.

Figure 3.16: MPX5700AP depth sensor with pin configuration [9]

3.6.3 10 DOF IMU Sensor

Figure 3.17 shows the 10 DOF IMU sensor is good at motion monitoring, detecting and measuring the position, height and temperature. It would be helpful for balancing robot by measure the heading degree of the AUV. Table 3.4 shows it consists of 3-axis accelerometer, 3-axis gyroscope, 3-axis digital compass and digital pressure sensor.

Table 3.3: Specifications of IMU sensor [3]

Power	3.3V–5.5V (internal voltage regulation)
L3GD20H 3-axis gyroscope Resolution : Measurement range (configurable) : Operating current :	 16 bit ±250, ±500, ±1000, ±2000°/sec 3.2mA

LSM303 3-axis compass	
Resolution :	14 or 16 bit
Measurement range (configurable) :	±4800μT
Operating current :	280uA
LSM303 3-axis accelerometer	
Resolution :	16 bit
Measurement range (configurable) :	±2, ±4, ±8, ±16g
Operating current :	450uA
BMP180 barometric pressure	
Resolution :	16~19 bit
Measurement range (configurable) :	300~1100hPa (altitude : +9000m~-500m)
Accuracy :	0.02hPa(0.17m)
PIN No.	
1 VCC	3.3V~5.5V power supply
2 GND	power ground
3 SDA	I2C data pin
4 SCL	I2C clock pin
5 INT	MPU9255 digital interrupt output
6 FSYNC	MPU9255 vertical sync signal

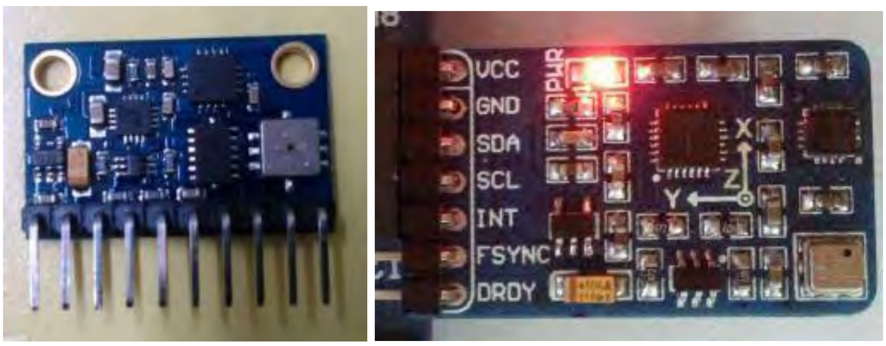


Figure 3.17: 10 DOF IMU sensor

3.6.4 Arduino Mega 2560

The AUV equipped with Arduino Mega 2560 as a main board to control the AUV shown in Figure 3.18. The microcontroller operates inside Arduino is an ATmega328. It has 54 digital input/output pins which 15 can be used as PWM outputs, 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. Figure 3.19 shows Arduino Mega 2560 board.

Figure 3.18: Arduino Mega 2560

3.6.5 Afro ESC 30A

Figure 3.19 shows Electronic Speed Control, ESC is a pre-programmed with custom firmware that allows motor move in forward and backward operation. The selected ESC is the model from BlueRobotics 30A as shown in Figure 3.20. This model was selected because it able to integrate with the brushless motor mentioned before and it also can provide constant current of 30 A. ESC will receive a signal from the Arduino Mega through the yellow wire (PWM signal). A stopped signal (1500 µs) is required for a few seconds to initialize the ESC.

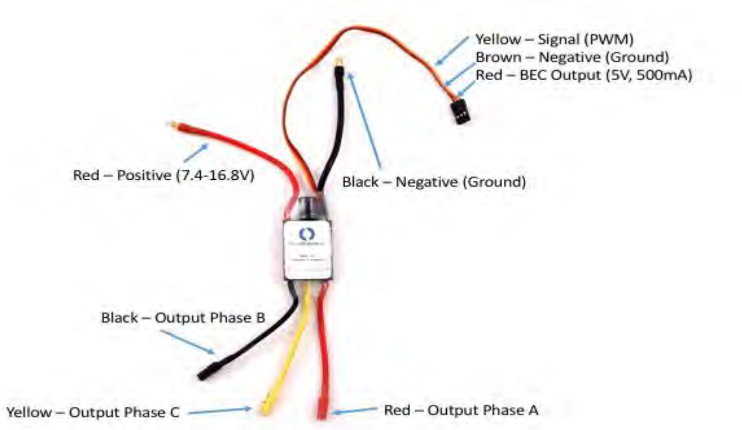


Figure 3.19: Afro ESC 30A [25]

3.7 Simulation Analysis Description

3.7.1 Simulation 1: Center of Mass (COM)

Objective: To determine and illustrate the center of mass and mass properties of the AUV

Procedure:

1. The assemble part is opened in SolidWorks.

2. In the drawing, click ‘Insert > Model Items Property Manager’.

3. Under Reference Geometry, click ‘Center of Mass’.

4. The position of the center of mass appears in the drawing.

5. The image of the center of mass is captured.

6. Click the mass properties tab and change the units to any suitable units.

7. The center of mass refers to 3 axes is recorded in the table.

3.7.2 Simulation 2: Stress and Strain Simulation

Objective: To illustrate and determine the deformation and stress of the AUV

Procedure:

1. The assemble part is opened in SolidWorks followed by Simulation Xpress.

2. Add a fixture by selecting the face model [inside hull] (show green arrows).

3. Add load by applying a force or pressure to the particular area on the model [outside hull] (show purple arrows).

4. Calculate the stress and displacement by selecting a material to the part/body.

5. The mesh setting can be changed between coarse and fine and run the simulation.

7 Next, either to ‘continue’ or ‘go back’ to edit the study parameters

8 Click ‘continue’, the ‘stress, displacement and factor of safety’ will show out

9. Finally, the report can be generated in either Microsoft Word or eDrawings format.

3.8 Experiment Implementation Description

The purpose of conducting the experimental test is to achieve the objective mentioned in the Chapter 1. There are six (6) experiment tests to be conducted include waterproof, balancing and buoyancy test in AUV hardware test while depth, speed and turning test for AUV performance test. The overview of equipment is described and shown in Figure 3.20.

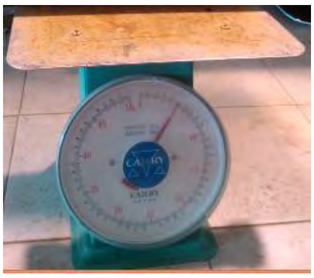
a. Rectangular Tap Water Pool at Underwater Lab FKE UTeM, dimensions as 2.4m length X 1.2m width X 0.7m height.
b. Rectangular Swimming Pool at Bukit Beruang Melaka, dimension as 18m length X 10m width X 2m height (only used a small part of pool).
c. Measuring Tape with 3m long.
d. Multimeter used to measure analogue value includes current, voltage flow from the sensor.
e. Weight Measuring Device with 50Kg maximum weight.

(a)

(b)

(c)

(d)



(e)

Figure 3.20: Equipments used in experimental tests

3.8.1 Experiment 1: Waterproof Test

Objective: To study and test the waterproof for the PVC pipe hull and Tupperware box AUV.

Parameters: Manipulated Variable: Time and Depth

Responding Variable: Level of water leakage

Apparatus: AUV, PVC pipe hull, Tupperware box, measuring tape.

Procedure:

1. The water is filled in pool to approximately 0.7 meter height.
2. Tupperware box is put inside the PVC pipe hull and close the end cap tightly.
3. The AUV is then submerged until around 0.5m from water surface as shown Figure 3.21.
4. It takes out from pool after 5 minutes and check whether the water flow in.
5. Step 2 to 4 is repeated with increasing the submerged period for 10, 15, 20 and 25 minutes.
6. Step 2 to 4 is repeated as changing time control of depth control by submerging it 0.1m from water surface for 10 minutes and follow by 0.2m, 0.3m, 0.4m, 0.5m and 0.6m.
7. The results then recorded and tabulated in table form.

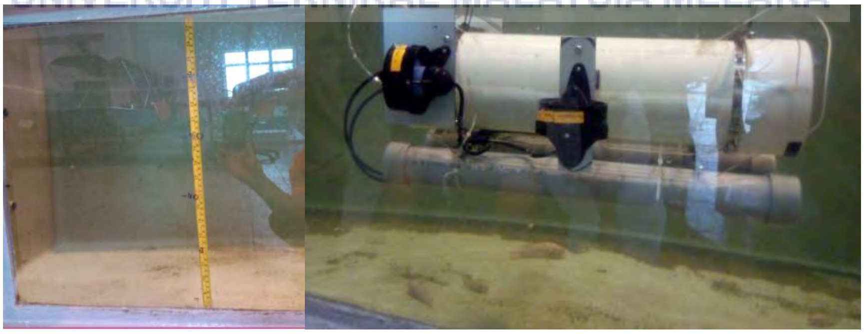


Figure 3.21: waterproof test of AUV

3.8.2 Experiment 2: Balancing Test

Objective: To study and determine the position of weight to balance AUV.

Parameters: Manipulated Variable: Weight

Responding Variable: Movement of AUV

Apparatus: AUV, PVC pipe, iron steel, weight measuring device.

Procedure:

1. The AUV is put into a lab pool without any weight attached and then balance it when floating.
2. 1Kg weight is put inside both PVC pipes respectively.
3. The AUV is then submerged until it reached stability, neither float nor submerge.
4. AUV is run with the weight attached to it. The forward movement of the AUV is observed whether it moves in a straight line.
5. Step 2 to 4 is repeated with increasing the weight for 2Kg, 3Kg, 4Kg and 5Kg and adjusting the position of iron steel inside the weight as shown in Figure 3.22.
6. The observation is then recorded and tabulated in table form.

Figure 3.22: Iron steel inside the weight

3.8.3 Experiment 3: Buoyancy Test

Objective: To study and measure the buoyancy force acting on the AUV.

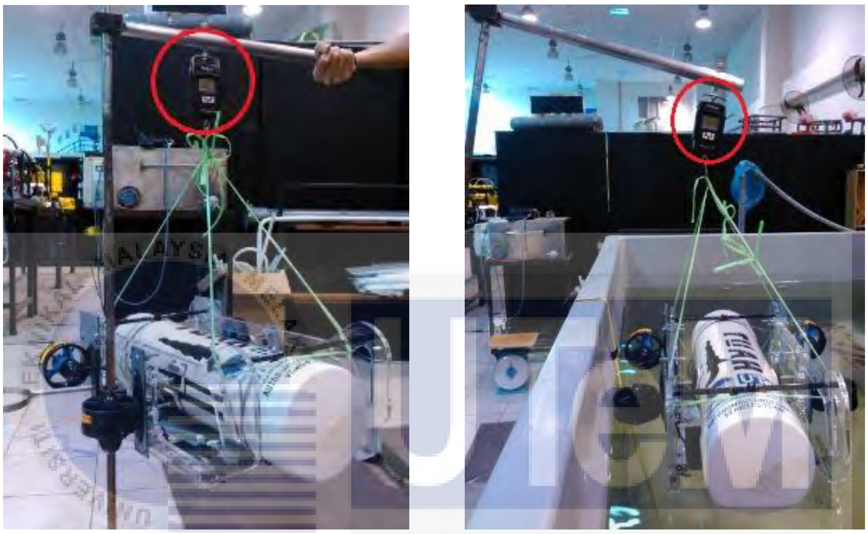
Parameters: Manipulated Variable: Weight/payload

Responding Variable: Buoyancy force (upward force)

Apparatus: AUV, PVC pipe, iron steel, weight measuring device.

Procedure:

1. The AUV is measured weight by hanging it from the string of weight measuring device without any weight attached as shown in Figure 3.23 (a).
2. While the AUV is still hanging from the device, submerge it in underwater pool but it is not touching the sides or bottom of the pool as shown in Figure 3.23 (b).
3. Step 1 and 2 is repeated by attached the weight to AUV with different mass.
4. The observation is then recorded and tabulated in table form.
5. Calculate the buoyant force by taking the difference between the mass (or weight) in air and the mass (or weight) in water.



3.23(a) 3.23(b)

Figure 3.23: AUV hanging by the weight measuring device

3.8.4 Experiment 4: Pressure (Depth) Test

Objective: To study and test the accuracy of pressure sensor (depth) in underwater.

Parameters: Manipulated Variable: Depth

Responding Variable: Voltage/pressure

Apparatus: Depth sensor (decoupling circuit), Tupperware box, measuring tape, USB cable.

Procedure:

1. The swimming pool used up to approximately 1.524 meter height as shown in Figure 3.24 below.

2. The pressure sensor is inserted into Tupperware box and connected to Arduino by using the long wire for serial monitor to computer.
3. The Tupperware box is then submerge into pool as shown in Figure 3.25 and pressure sensor will start detecting the pressure value.
4. The output signal voltage of depth sensor is measured by using multimeter.
5. The readings are taken three times to get more accurate results. These readings are considered as the 0 cm of water depth since the integrated sensor is placed on the water surface.
6. Step 3 to 5 is repeated by changing the depth of the sensor to different depth level.
7. The observation is then recorded and tabulated in table form.
8. A graph of comparison between theoretical and actual pressure measured by sensor is plotted and also the output voltage obtained from sensor.

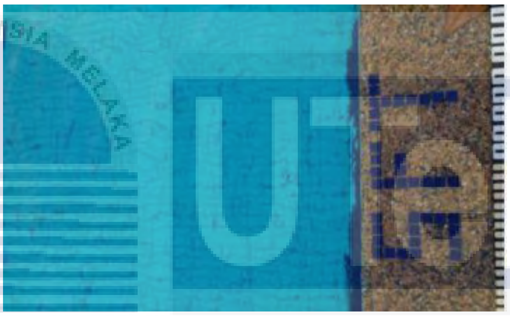


Figure 3.24: Swimming pool depth (5 feet = 1.524 meter)

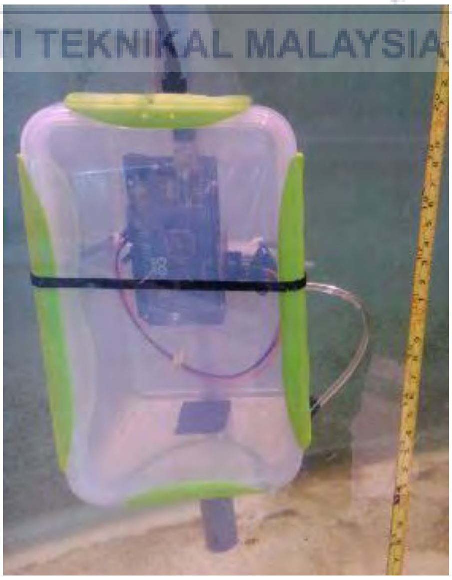


Figure 3.25: Tupperware with depth sensor put underwater

3.8.5 Experiment 5: Speed Test

Objective: To measure and determine the speed of AUV.

Parameters: Manipulated Variable: PWM, distance

Responding Variable: Time measured

Apparatus: AUV, measuring tape, stopwatch.

Procedure:

1. All the equipment includes weight and sensors were attached in the AUV.
2. The swimming pool is marked in 1m, 2m, 3m, 4m, 5m, 6m, 7m, 8m, 9m and 10m.
3. AUV is accelerated with 1600 forward PWM and the time taken for AUV move within 10m long is recorded as shown in Figure 3.26.
4. Step 3 is repeated by changing the forward PWM to 1700; backward PWM 1300 and 1400 for 5 meters long.
5. The observation is then recorded and tabulated in table form.
6. A graph of distance versus time is plotted and analysed.

26(a) [Starting point] 26(b) [Red circle indicated 10 meters]

Figure 3.26: AUV speed test at swimming pool

3.8.6 Experiment 6: Turning Test

Objective: To measure and determine the left and right turning speed of AUV.

Parameters: Manipulated Variable: PWM

Responding Variable: Time measured

Apparatus: AUV, measuring tape, stopwatch.

Procedure:

1. All the equipment includes weight and sensors were attached in the AUV.
2. AUV is turn left when thruster left move with 1600 forward PWM but thruster right stop and the time taken for AUV to turn 9 ◦ is recorded as shown in Figure 3.27.
3. Step 3 is repeated by changing the PWM to 1650, 1700, 1750 and 1800.
4. Step 3 to 4 is repeated by changing the turning direction from left to right.
5. Step 3 to 6 is repeated by changing the lab pool to swimming pool which is deeper.
6. The observation is then recorded and tabulated in table form.

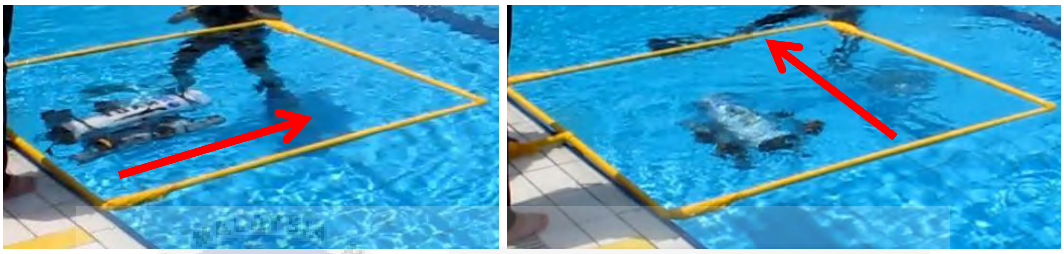


Figure 3.27: AUV turning speed test at swimming pool

3.9 Summary

As a summary, this chapter described the mechanical and electrical systems of the AUV that was designed and developed. The flow of the AUV projects from the starting to the ending is included and illustrated in different flowcharts. Besides, the procedure on the drawing and design was discussed in SolidWorks. Finally, the guideline on how to carry out different analysis in SolidWorks simulation and experiments were listed out in the final part of Chapter 3.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter study all simulations and results obtained will be included. Basically, the discussion and explanation of the results obtained was recorded in the Chapter 4. The results obtained are tabulated in either table or graph form to provide a better understanding toward the results taken.

In the first part, the results obtained from the analysis in SolidWorks are analysed and discussed. The analysis done in SolidWorks included center of mass, stress and strain.

The experiments on the AUV part hardware are included. The experiment tested for the AUV part is the waterproof for AUV electronic enclosure box, balancing of the AUV and buoyancy of the AUV. Next, the depth, speed and turning test prepare for the performance of the AUV. The data or results obtained are analysed based on the graph, table and figures.

4.2 SolidWorks Analysis

4.2.1 Analysis 1: Center of Mass (COM)

The purpose of this analysis is to find out the center of gravity or as known as the center of mass of the AUV. Center of gravity does not appear in SolidWorks by default, but it can be shown in drawing by following the procedures stated in the previous chapter. This application calculates properties include mass, density and volume constructed model geometry and material things. Center of gravity is a geometric stuff for any item and typical position of the weight of an object. Basically, these processes for determining the center of gravity is hard due to mass (and also weight) are not always same disseminated thru the design. The location of the center of gravity is an essential parameter to determine the AUV characteristics of an object as shown Figure 4.1. Controlling the AUV required good knowledge of its center of gravity location.

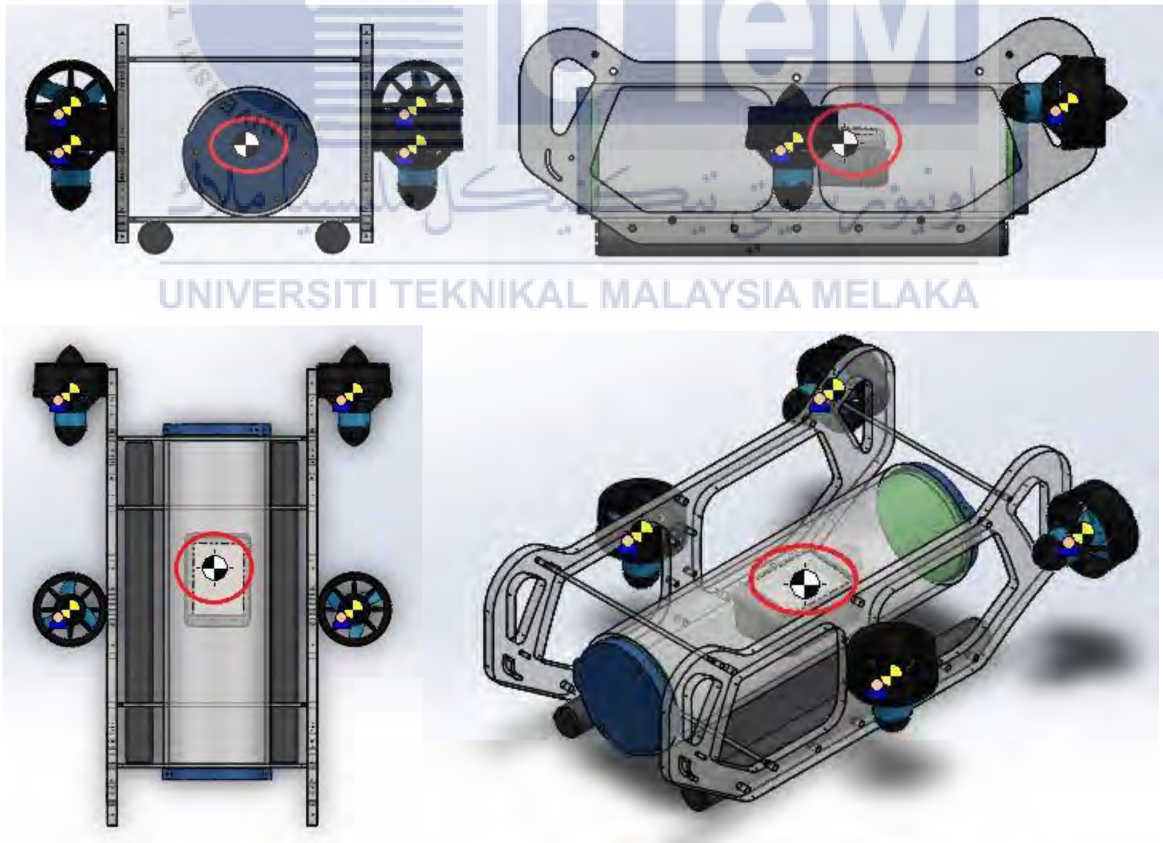


Figure 4.1: Different view of AUV center of mass

Table 4.1: Center of mass in SolidWorks Mass Properties

Axis	Coordinates (cm)
X	69.11
Y	2.74
Z	30.79

Based on the mass properties Table 4.1, it’s clearly shown that the centerr of mass for AUV is placed at 69.11cm X-axis, 2.74cm Y-axis and 30.79cm Z-axis. The COM also simulate for AUV mechanical parts include frame, hull, enclosure box and thruster.

Mass properties of AUV Assembly

Mass = 5501.02 grams

Volume = 5232.97 cubic centimeters

Surface area = 13836.38 square centimeters

Center of mass: (centimeters)
X = 69.11
Y = -2.74
Z = -30.79

Principal axes of inertia and principal moments of inertia: (grams * square centimeters)
Taken at the center of mass

Ix = (0.04, 0.08, 1.00)	*Px* = 1394185.59
Iy = (1.00, 0.00, -0.04)	*Py* = 1429473.88
Iz = (0.00, 1.00, -0.08)	*Pz* = 2510395.19

Moments of inertia: (grams * square centimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 1429402.68	*Lxy* = 295.67	*Lxz* = 1565.81
Lyx = 295.67	*Lyy* = 2503927.98	*Lyz* = 84713.92
Lzx = 1565.81	*Lzy* = 84713.92	*Lzz* = 1400724.00

Moments of inertia: (grams * square centimeters)
Taken at the output coordinate system

Ixx = 7820814.54	*Ixy* = -1264963.18	*Ixz* = -14235021.64
Iyx = -1264963.18	*Iyy* = 40807095.55	*Iyz* = 648291.19
Izx = -14235021.64	*Izy* = 648291.19	*Izz* = 33412654.16

4.2.2 Analysis 2: Stress and Strain Simulation

The stress and strain of the prototype AUV are simulated for the structural analysis in SolidWorks by the Finite Element Analysis (FEA) simulation Xpress. For this project, AUV used aluminium alloy 6061 as the main material for the frame, hull, box and others. This software used to analyse the property of safety factors, strain and stress. The purpose of the analysis is to predict the overall performance of the AUV mechanical construction under the water pressure at the operating depth environment. The pressure acting on the submerged part depends on the depth.

By using this FEA simulation Xpress, the deformation and stress distribution on each layer of materials can be analysed. The procedure of this analysis is described in the previous chapter. The geometry of the hull is first determined as shown in Table 4.2. Different fixture and pressure exerted to the hull is being simulated. Next, the remaining mechanical parts also undergo this simulation and the result will show in Appendix.

Table 4.2: Model Information (Hull)

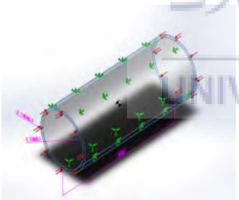
Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Scale1 	**Solid Body**	**Mass:2.76396 kg Volume:0.00102369 m^3 Density:2700 kg/m^3 Weight:27.0868 N**	**C:\Users\Wei Chiang\Desktop\BEKU4792 FYP1\Mechanical Part Design\AUV\Hull.SLDPRT Dec 05 19:19:55 2016**

Table 4.3: Material Properties (Hull)

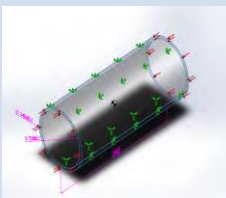
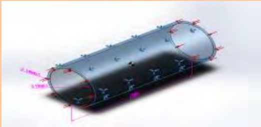
Model Reference	Properties	Components
	Name: 6061 Alloy Model type: Linear Elastic Isotropic Default failure criterion: Max von Mises Stress Yield strength: 5.51485e+007 N/m^2 Tensile strength: 1.24084e+008 N/m^2	SolidBody 1(Scale1)(Hull)

Table 4.4: Load and Fixtures definition

Fixture name	Fixture Image	Fixture Details
Fixed-1		Entities: 1 face(s) Type: Fixed Geometry

Load name	Load Image	Load Details
Pressure-1		Entities: 1 face(s) Type: Normal to selected face Value: 101325 N/m^2

Table 4.5: Mesh Information

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	0.430077 in
Tolerance	0.0215038 in
Mesh Quality	High

Table 4.6: Mesh Information Details

Total Nodes	15086
Total Elements	7515
Maximum Aspect Ratio	5.332
% of elements with Aspect Ratio < 3	96.5
% of elements with Aspect Ratio > 10	0
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	00:00:02

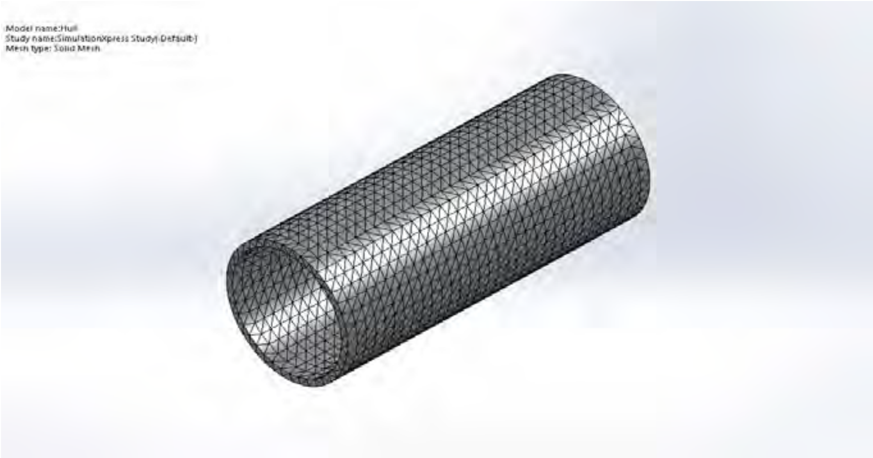
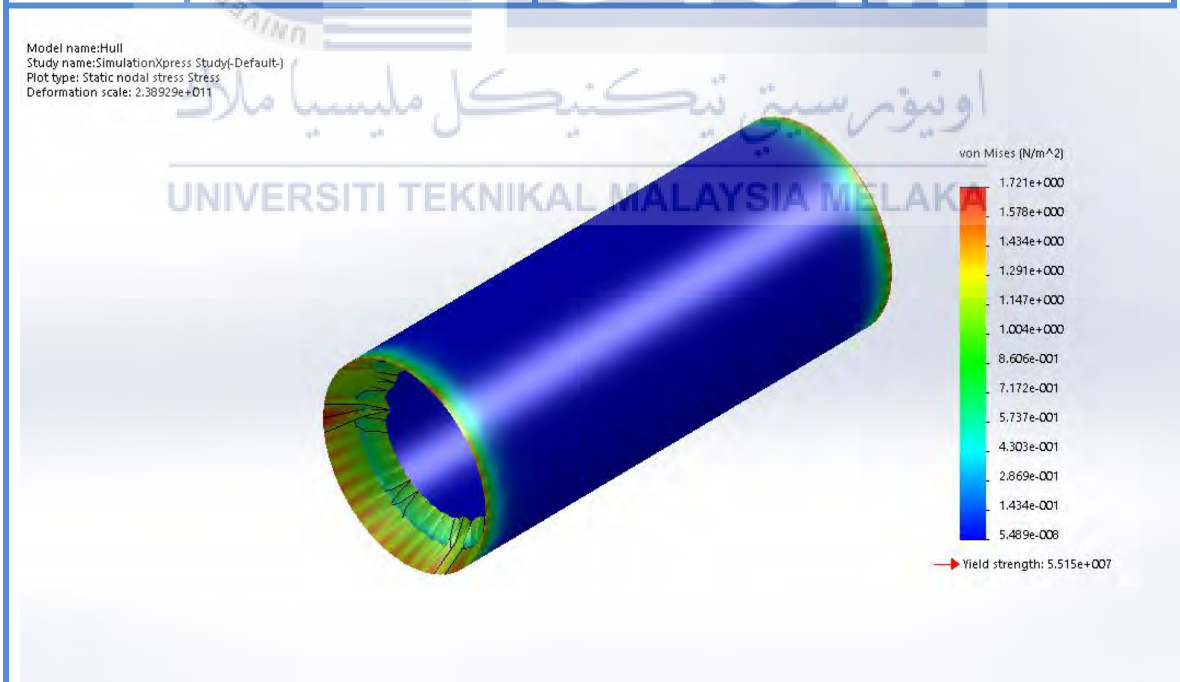


Figure 4.2: Meshing Results

Table 4.7: Study Results for Stress

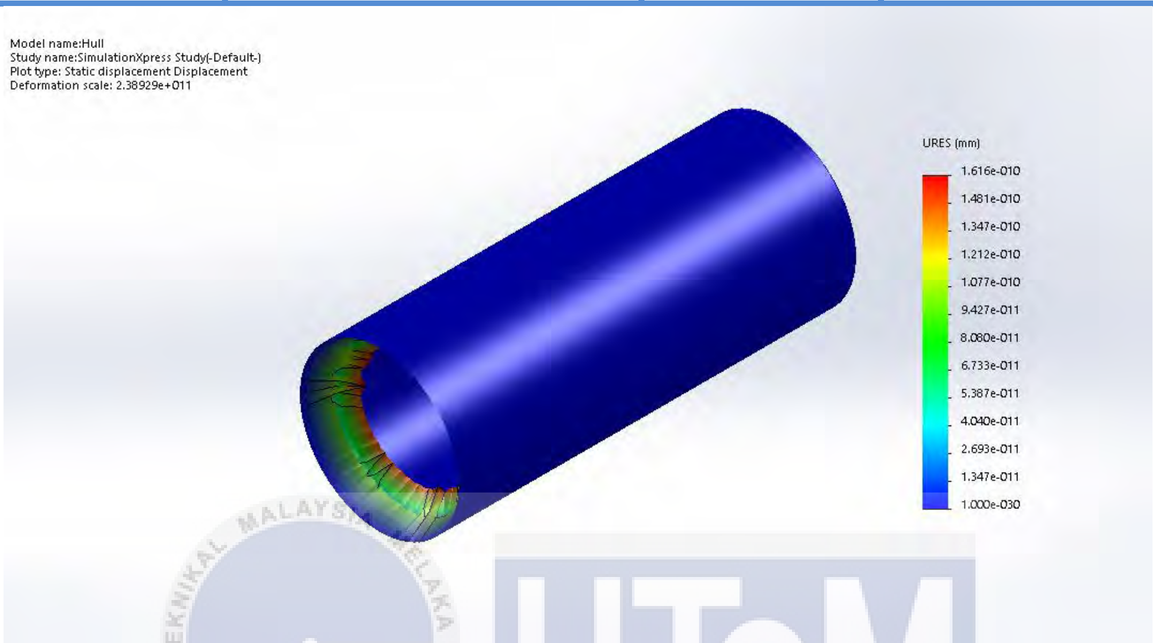
Name	Type	Min	Max
Stress	VON: von Mises Stress	5.48881e-008 N/m^2 Node: 7094	1.72121 N/m^2 Node: 1294



Hull-SimulationXpress Study-Stress-Stress

Table 4.8: Study Results for Displacement

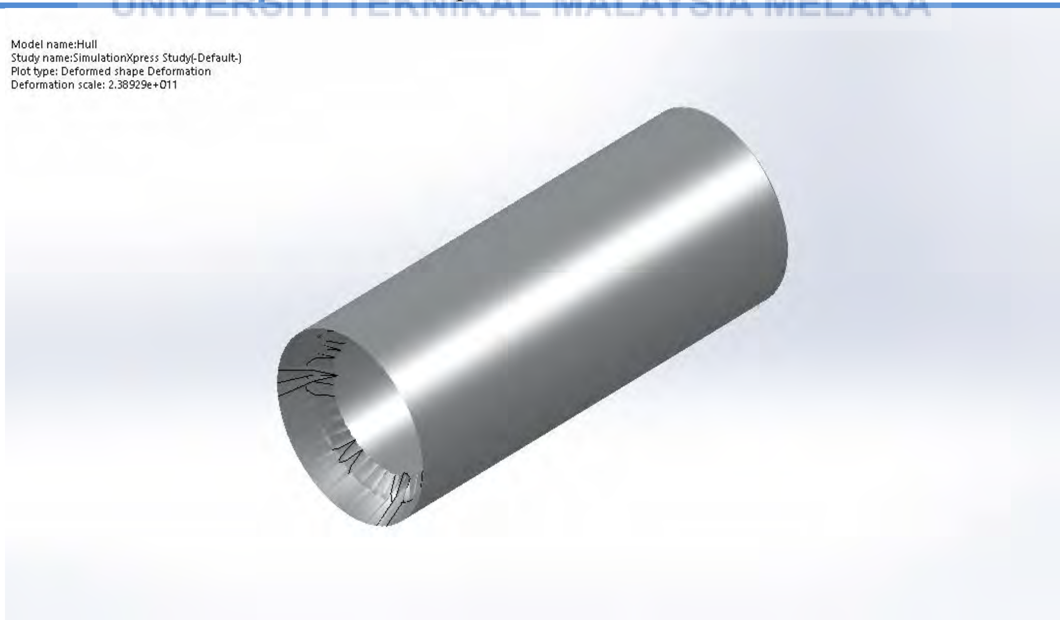
Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0 mm Node: 20	1.61603e-010 mm Node: 1



Hull-SimulationXpress Study-Displacement-Displacement

Table 4.9: Study Results for Deformation

Name	Type
Deformation	Deformed shape



Hull-SimulationXpress Study-Displacement-Deformation

Table 4.10: Study Results for Factor of safety

Name	Type	Min	Max
Factor of Safety	Max von Mises Stress	3.20405e+007 Node: 1294	1.00474e+015 Node: 7094

Hull-SimulationXpress Study-Factor of Safety-Factor of Safety

Table 4.2 and 4.3 show the pressure hull has a 2700 Kg/m^3 in density (2.76396 Kg, 0.00102369 m^3) with 5.5x10^7 N/m^2 in yield strength and 1.2x10^8 N/m^2. The fixture and load with 101.325 kN/m^2 pressure exerted in the fixture of the finite element analysis is shown in Table 4.4. The mesh property is shown in Table 4.5 and 4.6 and the meshing visualization displayed in Figure 4.2. Some of the study tests is simulated include the stress simulation (Table 7), displacement simulation (Table 8), deformation simulation (Table 9) and safety factor simulation (Table 10).

117.546 N/m^2 is the maximum stress (since only 101.325 N/m^2 is applied). By referring to the safety factor the material is fully safe since in blue colour. Since Al 6061 alloy has a 2700kg/m^3 density and 5.51485e+007 N/m^2 yield strength,

0 meter depth (surface) =1 atmospheric pressure =14.7 psi = 101.325 kPa = 101.325 kN/m^2

10 meter depth =2 atmospheric pressure =29.4 psi = 202.650 kPa = 202.650 kN/m^2

Given yield strength = 5.515x 10^4 kN/m^2 = 55150 kPa,

$$\frac{x}{10} = \frac{55150}{202.650}$$

x = 2721.4 meter sea depth

Table 4.11: Relation between water depth and water pressure

Depth (m)	Pressure (kPa)	Maximum Stress (kPa)
0	101.3250	117.546
1	111.4575	129.300
2	121.5900	141.055
3	131.7225	152.810
4	141.8550	164.564
5	151.9875	176.319
6	162.1200	188.073
7	172.2525	199.828
8	182.3850	211.583
9	192.5175	223.337
10	202.6500	235.092
3215 (Start to break)	65150	75579.7

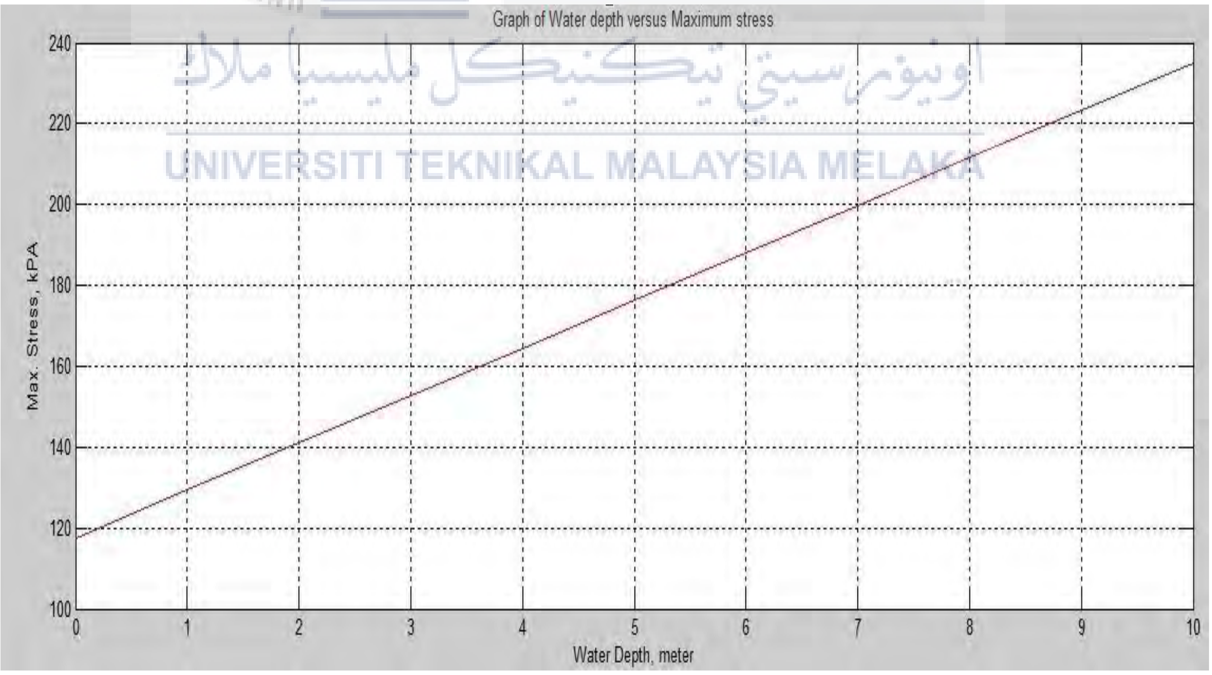


Figure 4.3: Graph of Maximum stress versus water depth

4.3 Experiment Results

4.3.1 Experiment 1: Waterproof Test

Results obtained from the experiment is recorded and analysed as shown in Table 4.12 and 4.13. The height (0.5m) of the lab pool is being measured to calculate the dimension and water pressure exerted. The equation is based on the fluid pressure principle which is

Pstatic fluid = ρgh where (ρ = fluid density; g = acceleration of gravity; h = depth of fluid)

= 1000 kg/m^3 X 9.81 N/kg X 0.5m

= 4.905 kN/m^2 (kPa)

Table 4.12: Waterproof Test for time controller (0.5 meter depth)

Time (minutes)	Waterproof	Water In
5	Yes	No
10	Yes	No
15	Yes	No
20	Yes	No
25	No but accepted	A little water flow in
30	No but accepted	A little water flow in

Table 4.13: Waterproof Test for depth controller (10 minutes)

Depth (meter)	Waterproof	Water In
0.1	Yes	No
0.2	Yes	No
0.3	Yes	No
0.4	Yes	No
0.5	Yes	No
0.6	No but accepted	A little water flow in

Based on Table 4.12, the hull of AUV able to blocks the water flow in within 20 minutes, after that a little water start to flow inside hull but not affected AUV to function. For depth controller in Table 4.13, water flow in about depth more than 0.6 meter but not affected AUV to function well. This is because all the electronic components put on the plate which is about 4cm high (Figure 4.4) and they also keep inside a Tupperware for double protection. Thus, these components are not to touch with water although water flow in. The water flow in due to frequently open and close the end cap for exchange Arduino coding and troubleshooting of components. Hence, white seal tape is used for enhancing waterproofing when close up the end cap.

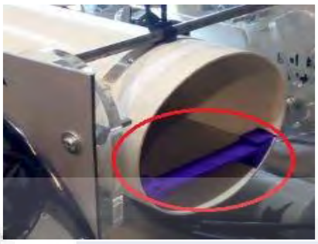


Figure 4.4 The plate inside PVC hull

4.3.2 Experiment 2: Balancing Test

After the addition of components and battery, the AUV center of gravity is changed. The reason of balancing test is to balance AUV back and make sure it moves in forward with straight line without any problems. Table 4.14 shows the observation for AUV balancing test with the forward motion.

Table 4.14: Observation of AUV forward movement

Weight (Kg)		**Balance**	**Observation**	**Adjustment**
Left	Right			
1	1	No	Moving to left direction Floating very fast	Adjusting the iron steel position and put more weight
2	2	No	Moving to left direction Fast floating	Adjusting the iron steel position and put more weight
3	3	Yes	Moving to left direction Floating medium speed	Adjusting the iron steel position and put some weight

4	4	Yes	Moving straight line Slowly floating	Adjusting the iron steel position and put more weight
4.8	5	Yes	Moving straight line Neither float nor submerge	Put foam to fixed the iron steel position and record the weight

From the observation in Table 4.14, AUV with different weights will have different results and cause unbalance motion. The weight contains iron steel inside the PVC pipe and tie together with AUV by cable ties. The unbalance position of iron steel inside pipe between both left and right causes the either side heavier, thus AUV move curve instead of straight line. Therefore, adjusting the position of iron steel should be make and fixed when its balance. Another reason that causes the unbalance is the position of components and battery. The position of the battery is in the front section of AUV while components are in the back section. It has caused the center of gravity to move front since battery heavier than components. To counter that, the iron steel weight should be fixed on the back side in pipe. Based on the experiment, it showed that AUV balance only when the weights are 4.8 Kg at left while 5 Kg at right as shown in Figure 4.5. Also, the AUV will be at the neutral buoyancy in underwater due to the equal between the gravitational force (weight) and the buoyancy force.

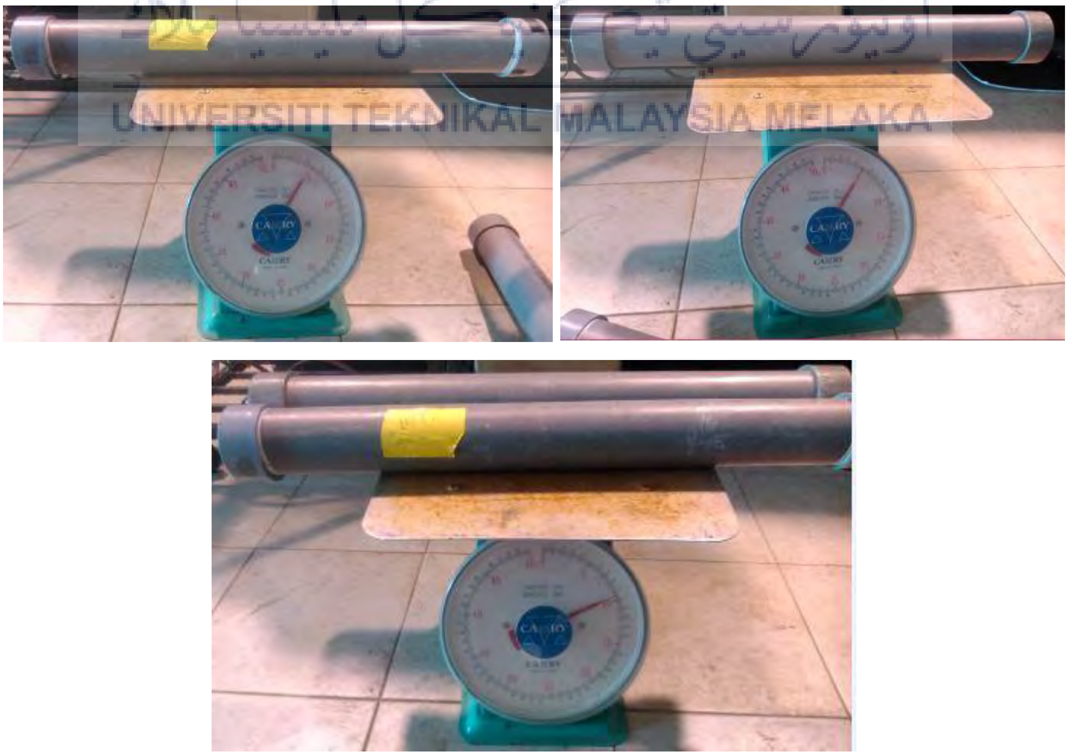


Figure 4.5: Weight for left, right and both

4.3.3 Experiment 3: Buoyancy Test

The buoyancy force of the AUV plays an important role to support the weight on the AUV. When an object is submerged in a fluid, the apparent weight of the object is less than the weight in air because of the upward buoyant force. Hence, the buoyant force B is found from the difference between the AUV's weight in air and its apparent weight in water with the Equation, B = W-T by using the value of the weight measured by the device. Tension, T is the opposite force upon to the weight (gravitational force).

Table 4.15: Buoyant force acting on AUV

Mass of AUV without weight attached = 8.20 Kg				
Mass of AUV attached with weight (Kg)		F = m*a (N)		
In air, m_1	In underwater, m_2	$W = m_1 * a$	$T = m_2 * a$	B = W-T
18	0.0	176.58	0.00	176.58
19	0.5	186.39	4.91	181.48
20	0.9	196.20	8.83	187.37
21	1.4	206.01	13.73	192.28
22	1.8	215.82	17.66	198.16

*** Acceleration due to gravity, a= 9.81m/s^2

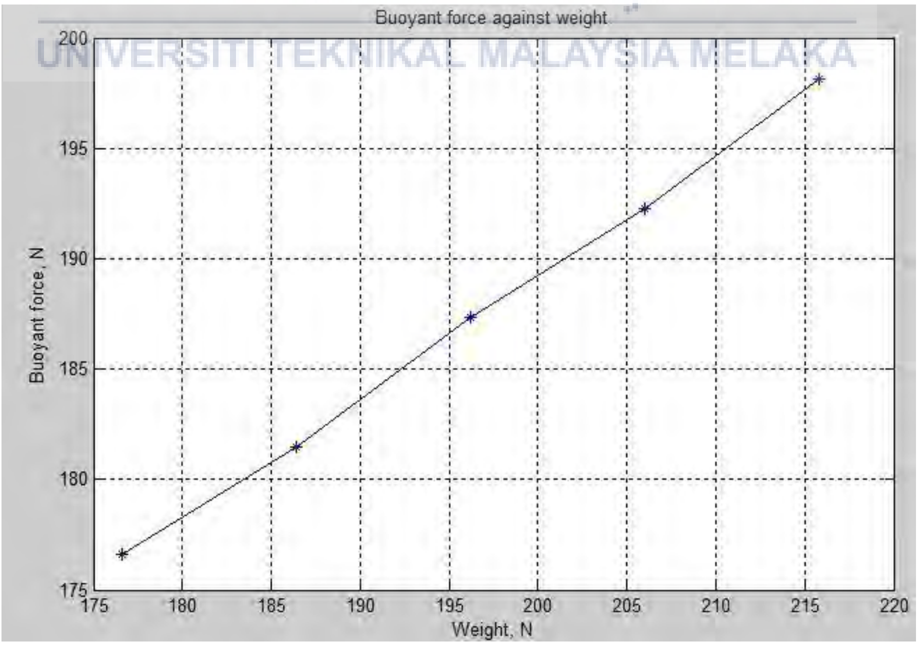


Figure 4.6: Graph of buoyant force against weight

Based on Table 4.15, the mass of AUV start with 18Kg since this is the equilibrium mass as it neither float nor sink. The maximum weight attached is 13.8Kg and the total is 22Kg due to the safety reason. The buoyant force does not depend on depth but depends on volume of the displaced fluid, density of the fluid and the acceleration due to gravity. Figure 4.6 shows the buoyant force increases as the weight attached increases. The purpose of attached weight to AUV was to increase the maximum weight and also the buoyant force. Thus, the addition of weight had successfully increased the buoyant force.

4.3.4 Experiment 4: Pressure (Depth) Test

The pressure sensor needs to be tested before used. The main purpose is to find out the accuracy of the pressure sensor and the percentage of error. After the pressure sensor had calibrated, AUV will have the accurate value for depth control. The output signal voltage is measured three times to get an accurate average output value. The manual measurement method used to measure the output signal voltage of depth sensor because the output signal voltage is very low. Table 4.16 shows the output signal voltage results with its depth.

Table 4.16: Output signal voltage

Depth (m)	**Measured Output Signal Voltage (V)**			
	1st	**2nd**	**3rd**	**Average**
0	0.863	0.864	0.862	0.863
0.1	0.874	0.871	0.868	0.871
0.2	0.875	0.879	0.877	0.877
0.3	0.881	0.883	0.885	0.883
0.4	0.888	0.889	0.887	0.888
0.5	0.891	0.893	0.895	0.893
0.6	0.896	0.902	0.899	0.899
0.7	0.907	0.905	0.903	0.905
0.8	0.910	0.912	0.908	0.910
0.9	0.917	0.916	0.915	0.916
1.0	0.924	0.920	0.922	0.922

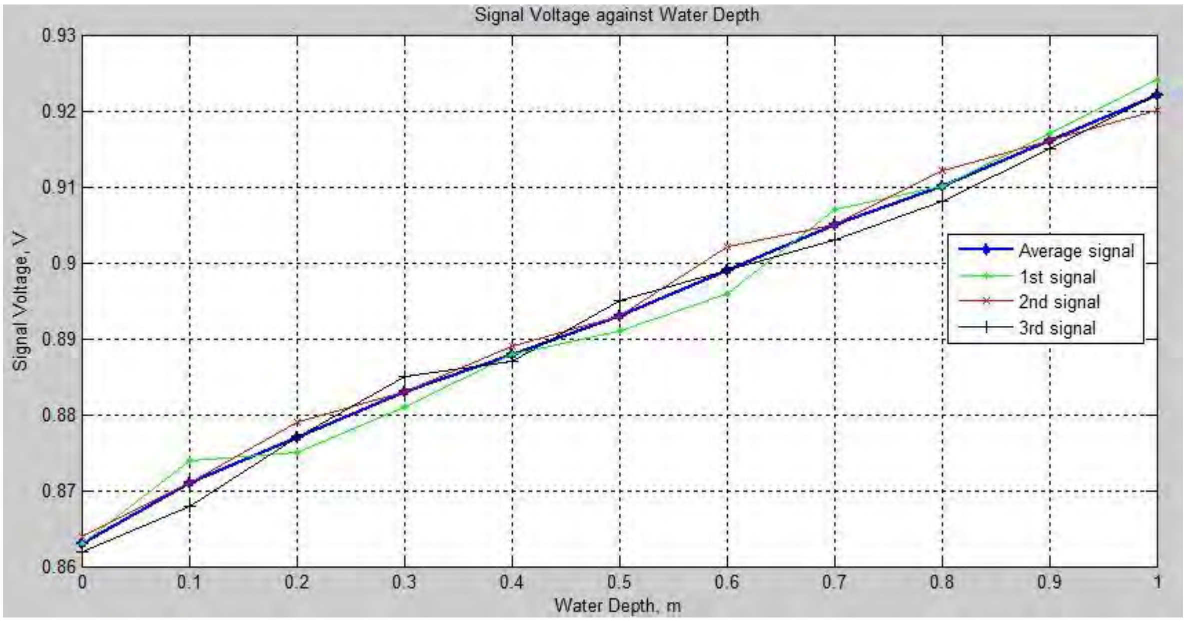


Figure 4.7: Graph of signal voltage against water depth

In Figure 4.7, the measured output signal voltage of the depth sensor is increases as the water depth increases until it saturated when the pressure sensor limit for the depth up to 70 meters. The three readings of output almost got same pattern that is linearly output. From Table 4.16 the setting depth between 0.863 V and 0.922 V is 1m. The theoretical pressure of this experiment can be obtained from the software converter that can be used to convert the water depth into pressure value. Figure 4.8 shows the software converter used to calculate the theoretical pressure at the given depth. The theoretical pressure can calculate by using equation (2.1) whereas actual pressure can calculate by using equation (4.2) and let Vs = 5V; Vout = average output voltage. Table 4.17 shows the value for actual and measured pressure and percentage of error.

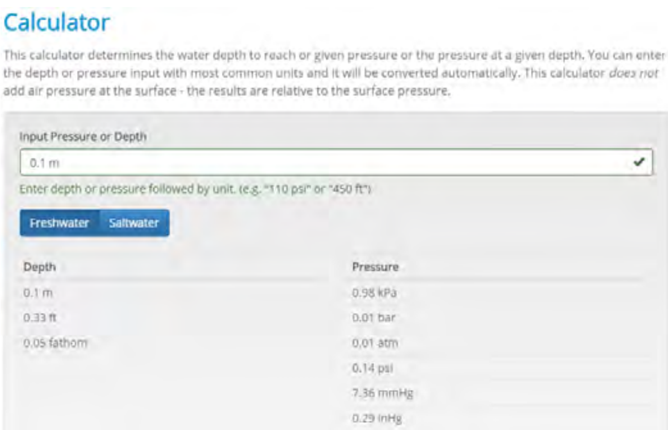


Figure 4.8: Pressure converter

$$\boldsymbol{Vout = Vs * (0.0012858 * P + 0.04)} \quad (4.1)$$

$$P = \frac{\frac{Vout}{Vs} - 0.04}{0.0012858} \quad (4.2)$$

$$Percentage\ of\ error = \frac{Actual\ \ pressure\ (kPa) - Measured\ pressure\ (kPa)}{Actual\ pressure\ (kPa)}\ X\ 100\% \quad (4.3)$$

Table 4.17: Actual and measured pressure

Depth (m)	**Actual pressure (kPa)**	**Measured pressure (kPa)**	**Percentage of error (%)**
0	101.33	103.13	1.78
0.1	102.31	104.37	2.01
0.2	103.29	105.30	1.95
0.3	104.27	106.24	1.89
0.4	105.25	107.02	1.68
0.5	106.23	107.79	1.47
0.6	107.22	108.73	1.41
0.7	108.20	109.66	1.35
0.8	109.18	110.44	1.15
0.9	110.16	111.37	1.10
1.0	111.14	112.30	1.04

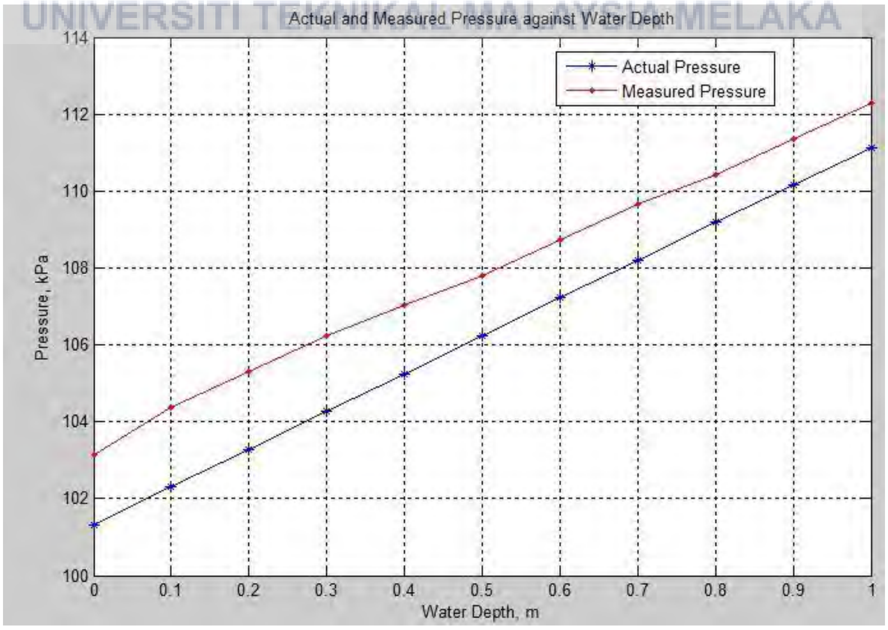


Figure 4.9: Graph of actual and measured pressure against water depth

From table 4.17, there are small error of the pressure sensor in pressure value due to environmental factor and interruption. When there is interruption in between the pulses, it will affect the efficiency of the sensor. Swimming pool contains some chemical substances like urine and chlorine cause the difference in terms of density. The performance of the MPX5700 depth sensor is acceptable in terms of percentage error which is under 3%. The analysis shows that it can accurately measure the pressure value in underwater since the actual water pressure value from the experiment is approximate to the theoretical water pressure value.

MPX5700AP every 25kPa give an output of 0.25V. It can measure up to 700 kPa equivalent to 71.38 meter deep as shown in Figure 4.10. It is suitable for more deep up to 70 meters. This pressure sensor can be applied in underwater vehicle to determine the depth of water based on changes in pressure. The change in depth will influence the pressure as defined in equation 4.4, p is pressure, w is weight of the fluid and h is the depth.

$$\Delta p = -w \Delta h \qquad (4.4)$$

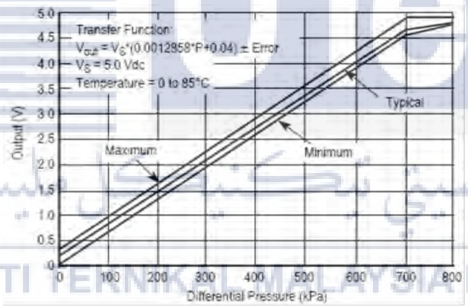


Figure 4.10: Output against absolute pressure (Datasheet)

As a conclusion, MPX5700AP pressure sensor shows a good performance to measure the pressure value in air and underwater. Besides that, it also can be used as a depth sensor for underwater vehicle in depth control application since it has a wide range of measurements.

4.3.5 Experiment 5: Speed Test

Speed test is one of the important tests to evaluate performance of AUV. For this experiment, the AUV was tested to find out its speed or velocity to move forward in the swimming pool since lab pool has limited distance and hard to measure the speed. The AUV is applied with different distance and PWM throughout the whole experiment.

Table 4.18: Speed test results

Distance (m)	1300		1400		1600		1700	
	Time (s)	Speed (m/s)	Time (s)	Speed (m/s)	Time (s)	Speed (m/s)	Time (s)	Speed (m/s)
0	0	0	0	0	0	0	0	0
1	3.3	0.303	3.5	0.286	3	0.333	2.5	0.400
2	6.3	0.317	6.8	0.294	5.6	0.357	4.6	0.435
3	9	0.333	9.8	0.306	8.1	0.370	6.7	0.448
4	11.5	0.348	12.6	0.317	10.6	0.377	8.7	0.460
5	13.8	0.362	15.3	0.327	13.1	0.382	10.6	0.472
6	-	-	-	-	15.5	0.387	12.5	0.480
7	-	-	-	-	17.9	0.391	14.4	0.486
8	-	-	-	-	20.3	0.394	16.3	0.491
9	-	-	-	-	22.7	0.396	18.1	0.497
10	-	-	-	-	25	0.400	19.8	0.505

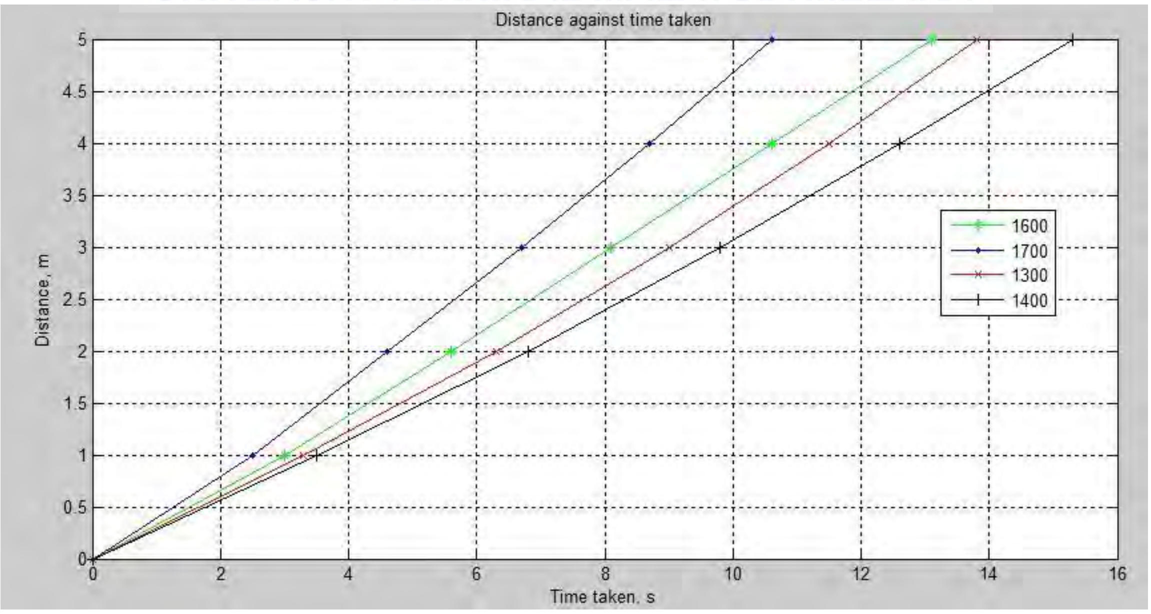


Figure 4.11: Velocity graph of AUV

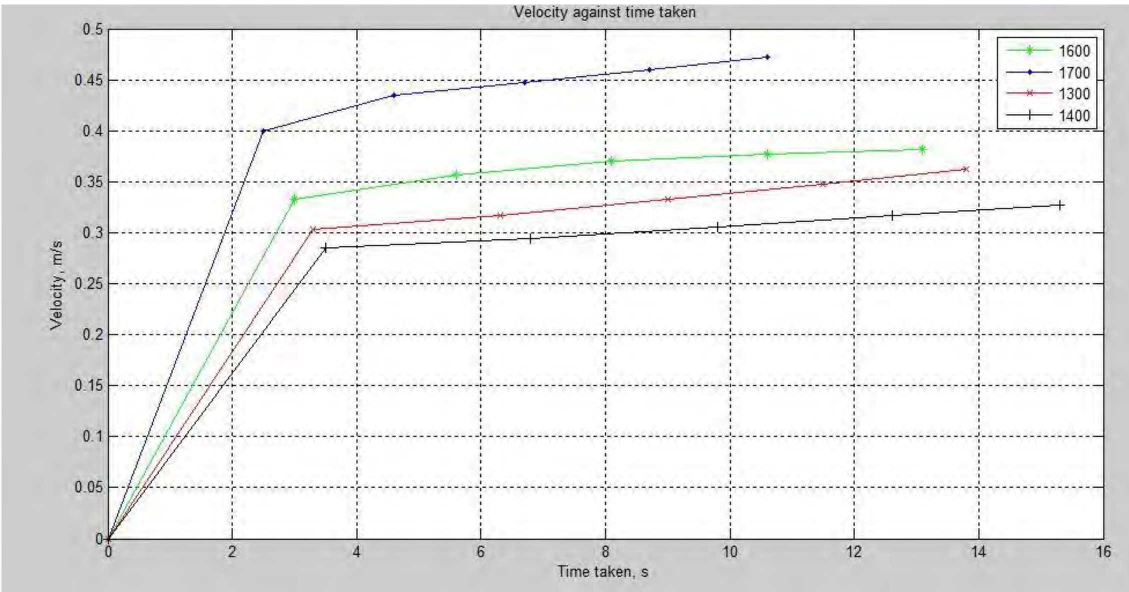


Figure 4.12: Acceleration graph of AUV

The velocity graph for 4 different PWM tests is plotted in Figure 4.11 and acceleration graph is plotted in Figure 4.12. Both graphs show that all 4 tests are with the distance increase linearly over time taken and velocity increase over the time taken. However, the voltage of battery supply drain faster as the PWM increase due to AUV has four T200 thrusters to move. This is a major problem for AUV to perform a faster speed in a long period.

In Table 4.19, the AUV moved forward for 10 m distance in 25 seconds with 1600PWM and 19.8 seconds with 1700PWM. This shows that using 1700PWM to programme AUV will save 5.2 seconds to complete a 10 m distance in forward direction. The AUV required greater force (higher speed) to push it when it started moved. Both PWMs show the speed increases as AUV moving further due to the inertia of AUV decreases. Based on Figure 4.11 and 4.12, both the velocity and acceleration graphs show that 1700PWM has the steeper slope (greater gradient) than 1600PWM. As the forward PWM of T200 thrusters increases, the velocity of AUV increases and has a higher acceleration.

For the same table, the AUV moved backward for 5 m distance in 15.3 seconds with 1400PWM and 13.8 seconds with 1300PWM. By using 1300PWM to programme AUV will save 1.5 seconds to complete a 5 m distance in reverse direction. The AUV required more time to push it moved in reverse direction compare to forward direction. Based on Figure 4.11 and 4.12, both the velocity and acceleration graphs show that

1300PWM has the steeper slope (greater gradient) than 1400PWM. As the backward PWM of T200 thrusters decreases, the velocity of AUV increases and has a higher acceleration.

4.3.6 Experiment 6: Turning Test

AUV was tested to find out its speed to move left and right in both pools. The AUV applied with different PWM throughout the whole experiment to turn in 9 ◦ left and right.

Table 4.19: Turning speed test in lab pool

PWM	Time taken for Turn Left (s)	Time taken for Turn Right (s)
1600	5	6
1650	4.5	5.3
1700	3.6	4.4
1750	3.1	3.7
1800	2.2	2.8

Table 4.20: Turning speed test in swimming pool

PWM	Time taken for Turn Left (s)	Time taken for Turn Right (s)
1600	5.2	6.1
1650	4.6	5.3
1700	3.6	4.5
1750	3.2	3.6
1800	2.2	2.9

For both tables, the time taken for AUV to turns in left and right decrease as the PWM increase. There is about 1 second faster between turn left compare to right due to the position of battery and components might not at the center position. This turning speed test concluded that it's able to function well in both lab pool and swimming pool If the AUV required to turns left, then the right thruster stop for it to move toward left direction and vice versa.

4.4 Modelling and Controller

4.4.1 System Identification Toolbox in MATLAB

For the dynamic control design of any systems, a suitable mathematical model is required. The AUV is modelled using the system identification toolbox in MATLAB to generate the transfer function for depth control. A dynamic model of the AUV is established based on the general motion of the AUV in six degrees of freedom includes heave, sway, surge, roll, pitch and yaw as a product of inertia, hydrodynamic and buoyant forces. This report only considers three axes for X, Y and Z directions depth regulation of AUV with the model of the AUV.

This tool used to generate transfer function modelling for depth control of AUV. The parameters obtained when the AUV submerge in the pool for 1m was inserted. The collected data from the Arduino serial monitor is transferred into Microsoft Excel file as shown in Table 4.21. Reading is chosen up to 25 seconds to analyse the model response. Depth input is the depth of AUV submerges by predicted and assumed while depth output is the actual depth of AUV submerges by processing of calculation in Arduino. The excel data is saved transferred to the workspace of MATLAB. The command "systemIdentification" is inserted in the command window of MATLAB to open the system identification tool. Import the data from the workspace to the system identification tool as shown in Figure 4.13.

Table 4.21: Depth data AUV

Time (s)	Depth input (cm)	Depth output (cm)
0	0	0
1	100	4
2	100	15
3	100	27
4	100	38
5	100	49
6	100	58
7	100	69
8	100	78

9	100	87
10	100	95
11	100	100
12	100	105
13	100	110
14	100	114
15	100	116
16	100	120
17	100	120
18	100	120
19	100	120
20	100	120
21	100	120
22	100	120
23	100	120
24	100	120
25	100	120

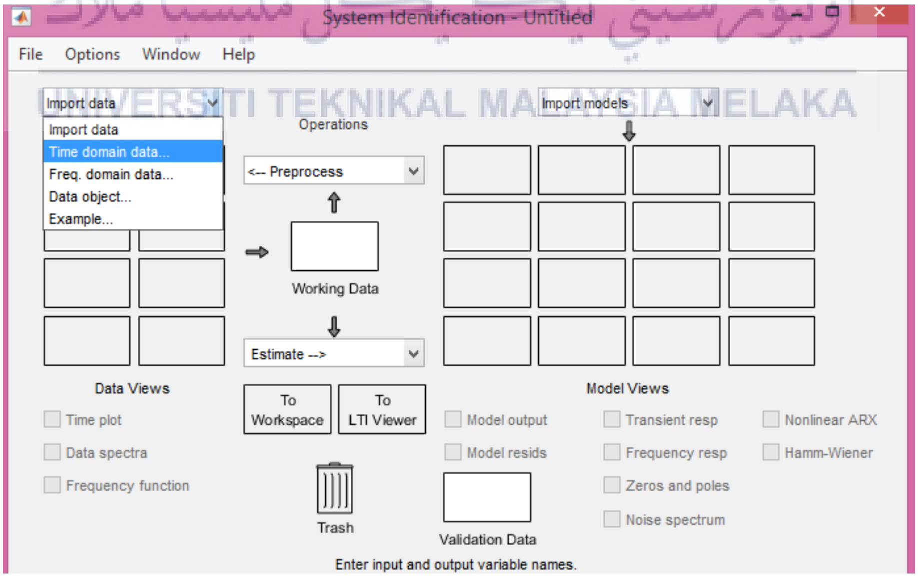


Figure 4.13: System Identification Toolbox

The workspace variable is inserted into the import data window and the starting time set to 0s and the sampling interval chosen to be 0.02s as shown in Figure 4.14.

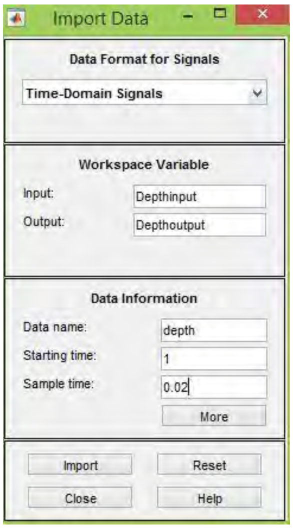


Figure 4.14: Import data

The time plot for input and output data is shown in Figure 4.15.

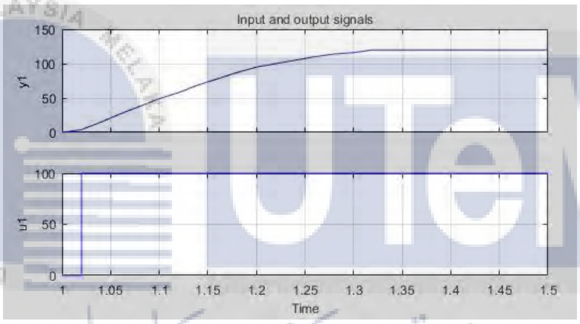


Figure 4.15: Time plot for both data

Next, the "Transfer Function Model" is chosen from the "Estimate" drop down list as shown in Figure 4.16.

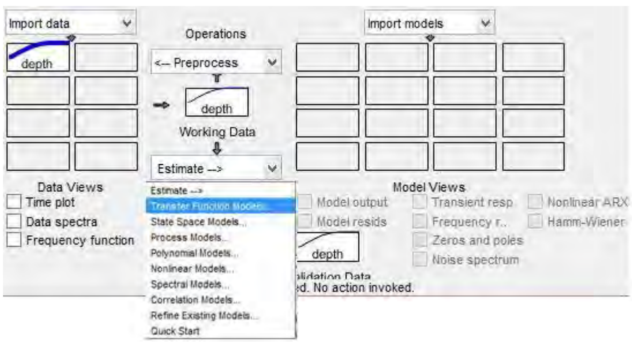


Figure 4.16: Transfer Function Model

The number of poles and zeroes are assigned to get the model response (Figure 4.17).

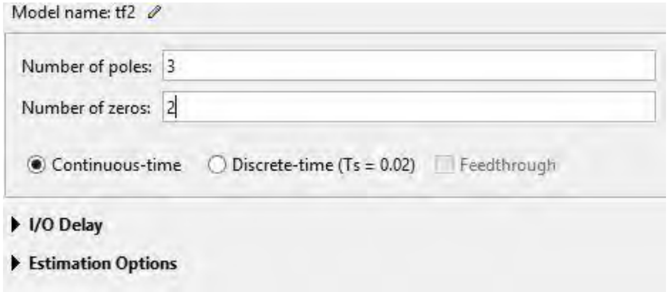


Figure 4.17: 3 Poles and 2 zero

Next, the plant identification progress did for estimate the transfer function. In the command window when the name of model is inserted which is "tf2", the transfer function for the model is displayed as shown in Figure 4.18. Figure 4.19 shows the step response for AUV and the best fits line shows 98.51% about the accuracy of this transfer function.

```
From input "u1" to output "y1":
  5.932 s^2 + 128.3 s + 2109
------------------------------
s^3 + 16.91 s^2 + 290.5 s + 1694
Name: tf2
Continuous-time identified transfer function.
```

Figure 4.18: Transfer Function Model

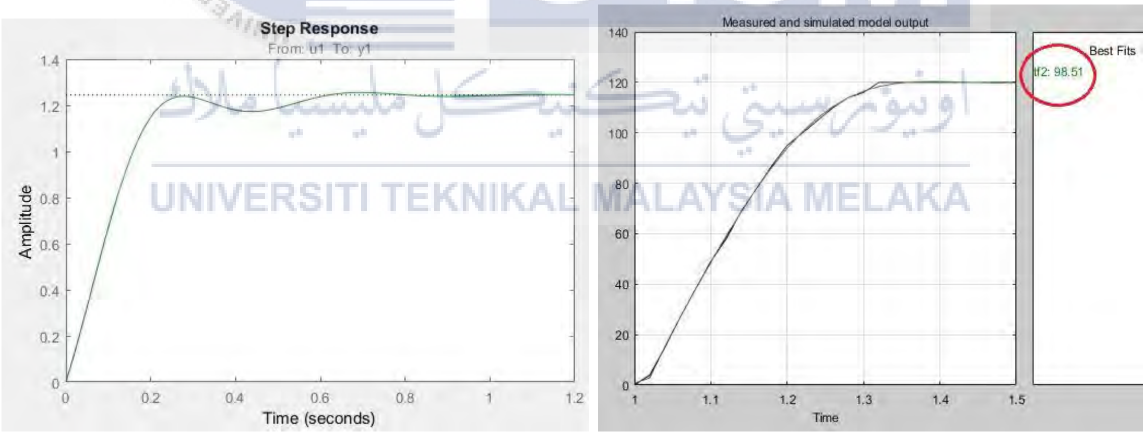


Figure 4.19: Step Response

For system identification system, three poles and two zeros are used to implement the three axes AUV depth motion. Based on the time plot graph, depth output is the actual depth of AUV submersion without any controller. It submerges freely and will stop stationary at 12 cm depth due to AUV's weight is almost equal to buoyancy force Thus, it required a controller to maintain it at 100 cm depth as a depth control system.

4.4.2 AUV Depth Controller (On-Off Controller)

On-Off (Bang Bang) Controller is the simplest controller by implement with the microcontroller coding. MPX5700 depth sensor is used to determine the actual depth and send to the Arduino Mega for processing the signal data and send back signals to ESC to actuated thruster to move downward (submerge). Arduino coding is written in the form of "if… else if…" condition to give the command for AUV in response in a different action. There are three selections for AUV in response include AUV move downward if depth less than 100cm; move upward if depth more than 100cm and stops if depth equal to 100cm.

Table 4.22: Depth data AUV for On-Off Controller

Time (s)	Depth input (cm)	Depth output (cm)
0	0	0
1	100	4
2	100	15
3	100	27
4	100	38
5	100	49
6	100	58
7	100	69
8	100	78
9	100	87
10	100	95
11	100	104
12	100	110
13	100	117
14	100	110
15	100	102
16	100	92
17	100	97
18	100	103
19	100	104
20	100	106

21	100	110
22	100	117
23	100	114
24	100	109
25	100	105

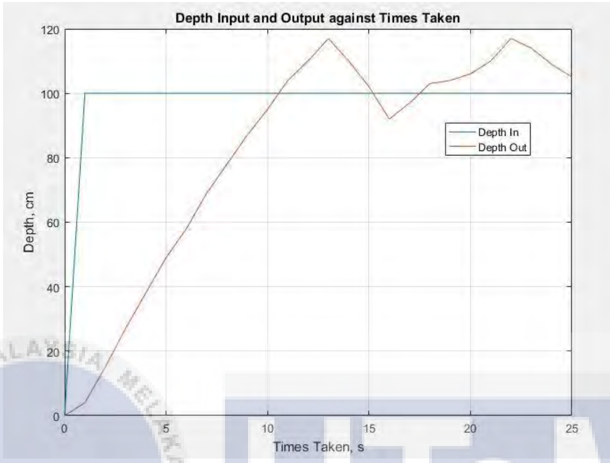


Figure 4.20: Graph of depth input and output against time

Based on the On-Off controller graph (Figure 4.20), it shows the unstable depth control system due to AUV moving downward and upward continuously. It moves downward when less than 100 cm, but it will not stop instantaneous when it reaches 100 cm due to its weight. Then, it moves upward to float until 100 cm but it will not reach accurately and these actions continue until it reaches 100 cm with a long time.

4.4.3 AUV Depth Controller (PID controller)

Proportional Integral Derivative (PID) controller is based on the feedback of a device or process, such as a depth controller is measured and compared with the target or set point. The proportional controls the correction factor while integral function addresses this by considering the cumulative value of the error while derivative function prevents a delay in response to the correction this leads to an overshoot as refer to Table 2.3 [26]. There are three tuning methods include manual tuning, heuristics tuning and auto tune.

MATLAB/Simulink block diagram for the AUV depth control system is designed and shown in the Figure 4.21. Then, the MATLAB/Simulink is run or simulate without any tuning to observe and analyse the original block response (*P*=1; *I*=1; *D*=0; *N*=100). Tune button is clicked to launch the PID tuning tool in PID window and wait for the system to tune Auto. Figure 4.22 shows the final value for PID parameters after auto tuning.

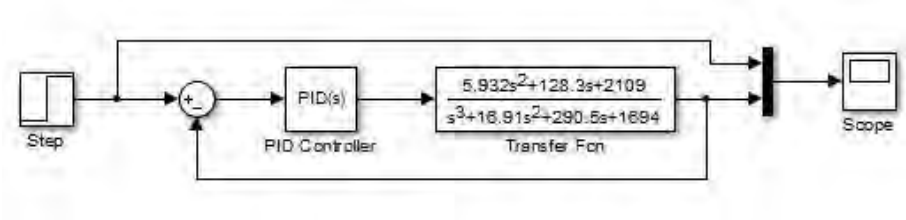
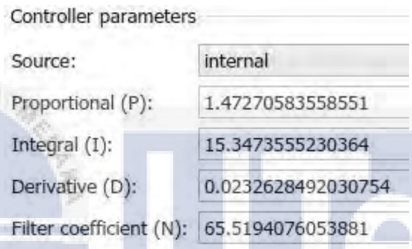


Figure 4.21: Simulink of PID for AUV depth control



Controller parameters	
Source:	internal
Proportional (P):	1.47270583558551
Integral (I):	15.3473555230364
Derivative (D):	0.0232628492030754
Filter coefficient (N):	65.5194076053881

Figure 4.22: PID function block parameters after tuning

For PID controller, Figure 4.23 shows the combination of three responses includes original step response (blue line), PID original tune response (black line) and after PID auto tuned response (pink line). Figure 4.24 shows the PID step response after tuning. Based on the Figure 4.25, there are differences between two response graphs in terms of rise time, settling time and other important parameters.

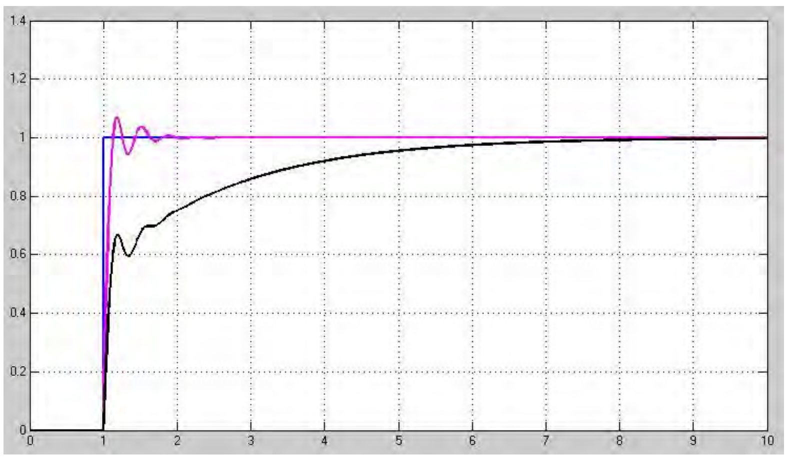


Figure 4.23: Original and PID response before and after tuning

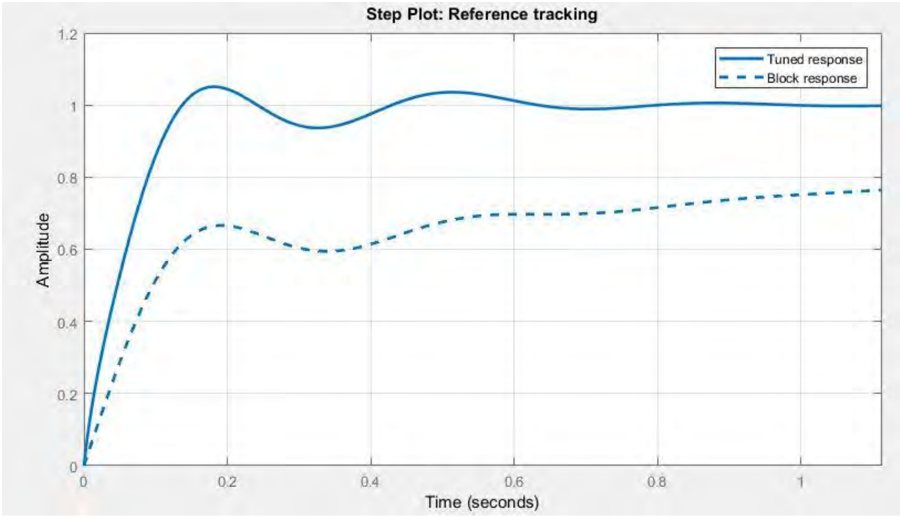


Figure 4.24: PID step response after tuning

Controller Parameters

	Tuned	Block
P	1.4727	1
I	15.3474	1
D	0.023263	0
N	65.5194	100

Performance and Robustness

	Tuned	Block
Rise time	0.102 seconds	2.59 seconds
Settling time	0.58 seconds	5.43 seconds
Overshoot	5.09 %	0 %
Peak	1.05	0.998
Gain margin	Inf dB @ NaN rad/s	Inf dB @ NaN rad/s
Phase margin	60 deg @ 18 rad/s	101 deg @ 13.5 rad/s
Closed-loop stability	Stable	Stable

Figure 4.25: PID tuning performance parameters

For this AUV PID depth controller, the auto tuning PID response is smoother, but higher overshoot compared to the PID original tuned response. Based on the parameters, PID auto tuned has faster rise time (0.102s) and settling time (0.59s) to achieve the peak compared to the PID original tuned response. However, AUV need to accurately submerge in underwater. Thus, the best result is the original PID controller as it has zero overshoot.

4.4.4 AUV Depth Controller (FLC Controller)

A Fuzzy Logic Controller (FLC) is designed to emulate human deductive thinking, that is, the process people use to infer conclusions (decision making) from what they know. FLC provides a means of converting a linguistic control strategy based on expert knowledge into an automatic control strategy. A sliding mode fuzzy controller was designed in [28] and made it ideal for time optimal robust control. A discrete-time quasi-sliding mode control of AUV was proposed in [29] and a simple 14 rule fuzzy logic controller was designed in [30]. FLC consists of four basic components include knowledge base, fuzzification, inference engine and defuzzification as shown in Figure 4.26.

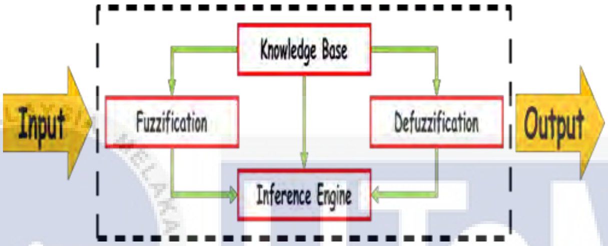


Figure 4.26: Basic Configuration of Fuzzy Logic Controller

In this project, a fuzzy inference system (FIS) editor is opened to change the setting of the controller as shown in Figure 4.27 with two inputs of the controller (depth error and differential error) The output that is used in this controller is 'output' The 5 x 5 membership function partitions are set and designed which are labelled as *NL*, *NS*, *Z*, *PS* and *PL*. A triangular type function is used for inputs and output partitions of the system to ease tuning.

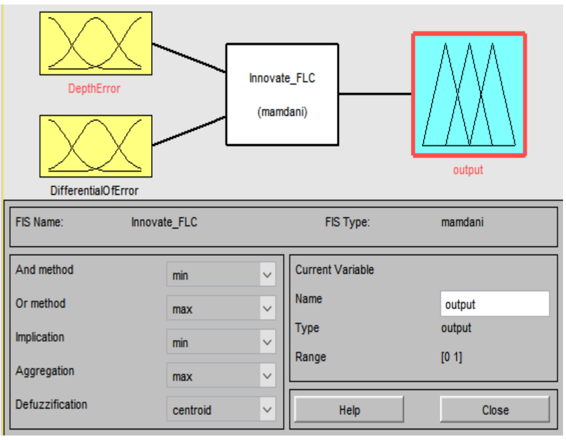


Figure 4.27: Fuzzy inference system (FIS) editor

Figure 4.28 are the membership functions for two inputs and one output respectively. Based on the inputs and output variables defined in the FIS Editor, the rule statements are constructed in the Rule Editor as shown in Figure 4.29 according to Table 4.23 The FIS editor is exported into a file named 'Innovate_FLC' and then exported to the workplace. The fuzzy logic controller in the Simulink also named the FIS file with 'Innovate_FLC '

Table 4.23: Rule table of FLC

Differential Error \ Depth Error	PM	PS	Z	NS	NM
NM	Z	NS	NL	NL	NL
NS	PS	Z	NS	NL	NL
Z	PL	PS	Z	NS	NL
PS	PL	PL	PS	Z	NS
PM	PL	PL	PL	PS	Z

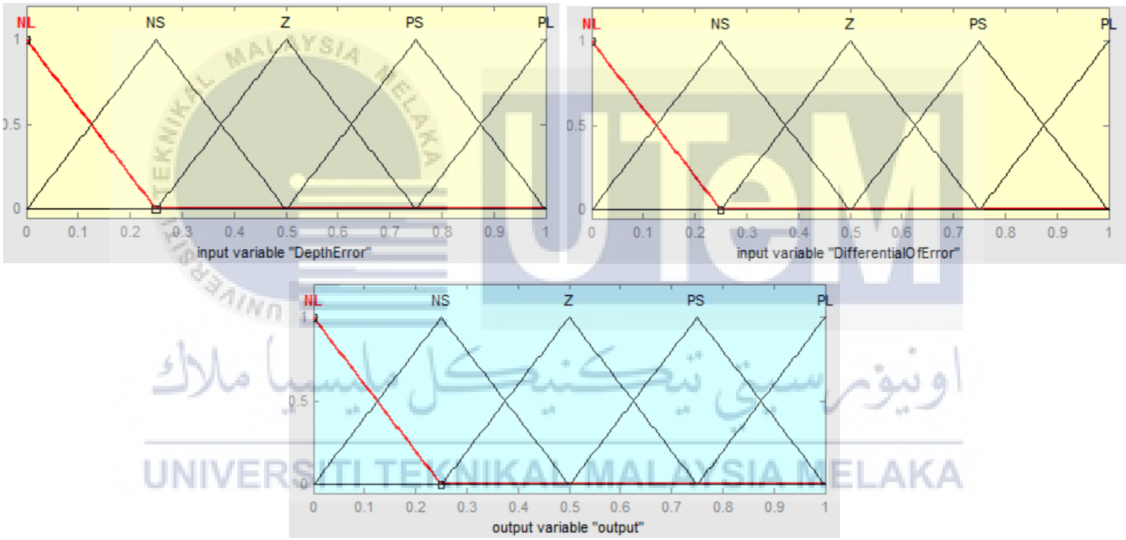


Figure 4.28: 'error', 'differential error' and 'output'

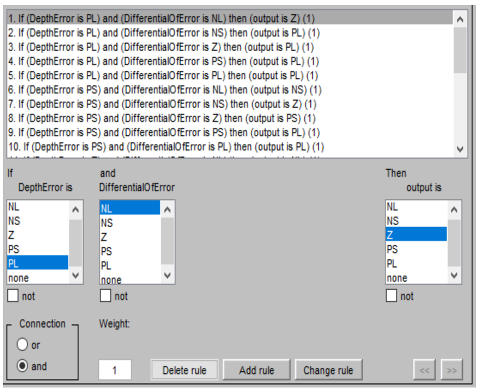


Figure 4.29: Rule editor of FIS

The MATLAB Simulink block diagram of the system is designed as shown in the Figure 4.30. Figure 4.31 shows the initial output response of the system, it does not follow the set point in the beginning, not run in a smooth line and even run in a low steady state value because there are some disturbances or noises in the response that will affect the system's stability There are three basic methods to tune the fuzzy system, such as scale of membership functions, mapping of membership function and adjusting rules. In this study, adjusting the mapping of output membership function is focused. The output membership functions are tuned and analysed until a satisfactory output response is obtained.

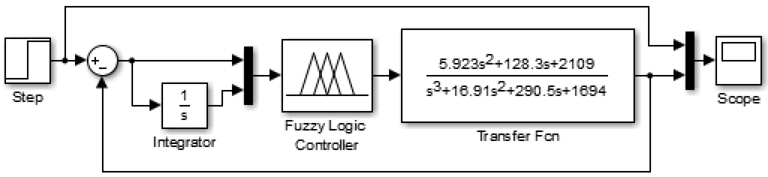


Figure 4.30: Simulink of FLC

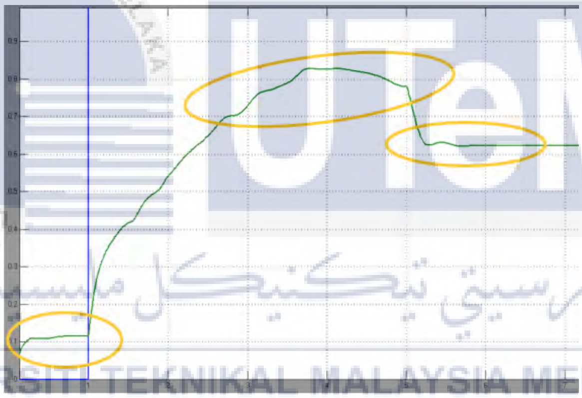


Figure 4.31: Initial output response of the system

Therefore, the *NL* partition is tuned since the *NL* partition is the starting process of system response as shown in Figure 4.32. There is only *NL* partition will be adjusted to left (25% of the range) until the output response follow the set point in the beginning. Figure 4.33 shows its output response after *NL* partition is tuned but still has a low steady state value and not run in a smooth line. Therefore, the mappings of the membership functions are adjusted via heuristic approach until to get the desired output response. To solve this problem, the others 4 of the membership functions (*NP*, *Z*, *PS* and *PL*) are moved to the right (25% of the range) and their scale factor is reduced (80%) as shown in Figure 4.34. The output response flows in a smooth line and the steady state value is increased as shown in Figure 4.35. The output response still needs to tune until the dropped signal is eliminated and flow in smooth.

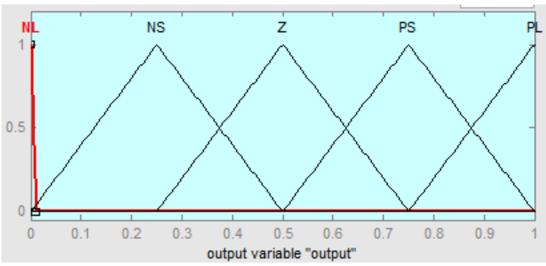


Figure 4.32: Membership function *NL* partition is moved to left

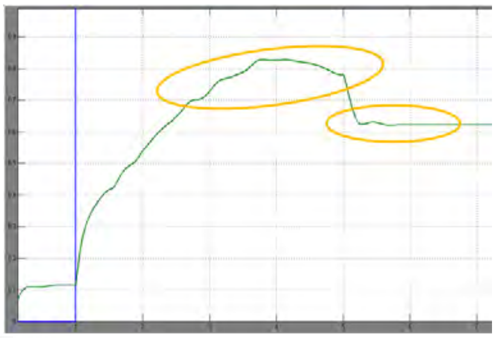


Figure 4.33: The output response after *NL* partition is tuned

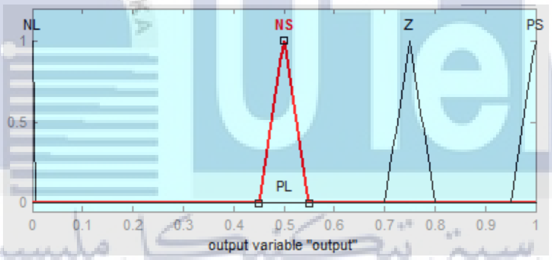


Figure 4.34: Reduce scaling factor and move to right

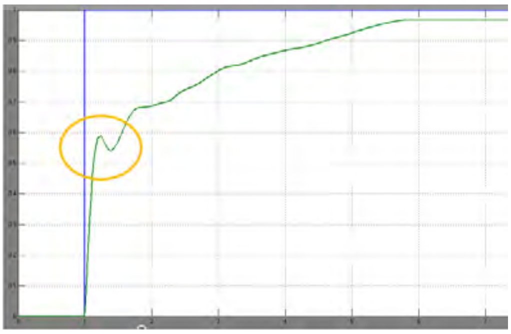


Figure 4.35: One dropped signal after tuning

For this AUV FLC depth controller, the summary of the tuning process is shown as Table 4.24. It is the guidelines to design and tune FLC. Every response will have its own way to tune and design. This means that there is no fixed solution, but it will give a good response as well as possible.

Table 4.24: Summary of the tuning process

Problem occurred	MF partition at output	Tuning
Noise at early response	NL	Shift to left (25% of the range)
Not in smooth response	NP or Z or PS or PL	Reduce scale (80%) and shift to right (25% of the range)
Low steady state value	NP or Z or PS or PL	Reduce scale (80%) and shift to right (25% of the range)

In Figure 4.36, the green line represents the FLC response, the pink line represents the PID response after auto tuned while the red line represents the PID response original tuned. Based on Figure 30, PID auto tuned controller (pink line) gives better response than FLC (green line) since the FLC (green line) is not tuned nicely in terms of rise time, settling time and peak time. As the peak and settling time decrease, the damping ratio will increase, the overshoot decreases. According to the results, PID control has good steady performance and high control accuracy, although it is easier to produce overshoot and long regulation time.

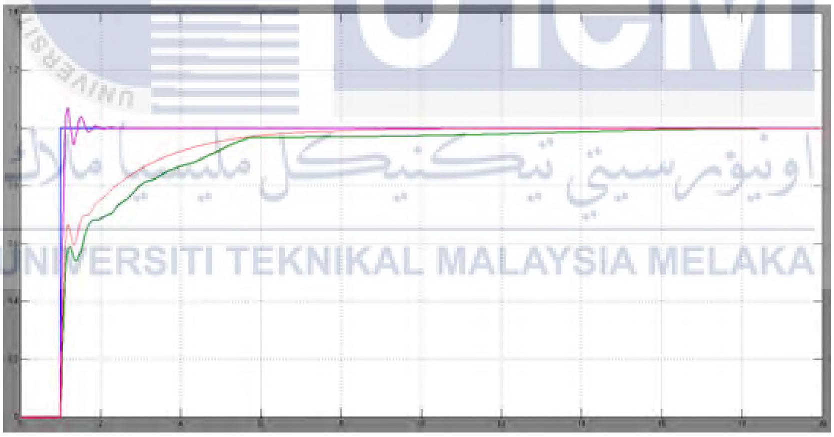


Figure 4.36: Output response of tuned PID and FLC

Table 4.25: Performances of the controller

Parameter	FLC	PID Tuned	PID Block
Rise time (s)	2.96	0.102	2.59
Settling time (s)	7.53	0.58	5.43
Overshoot (%)	0	5.09	0
Peak	0.968	1.05	0.998
Peak time (s)	6.109	1.186	7.120

Table 4.25 shows the comparison parameters for three different response plots. In depth motion control (vertical trajectory), overshoot of the system response is the most important parameter and also one of the factors to be measured because overshoot is particularly dangerous in the AUV vertical trajectory and may give damage to AUV and inspected structure. In terms of rise time, settling time and peak time, PID auto tuned response is the best response among the controllers. However, it generates overshoot (5.09%) while the FLC and PID original tuned responses do not generate any overshoot in the system response. However, in terms of rise time, settling time and peak time, PID original tuned gives better response than FLC.

4.5 Summary

Overall, Chapter 4 discussed about the results obtained from the analysis in SolidWorks and also experiments. The analysis done in SolidWorks included center of mass, stress and strain and sustainability. Results obtained are either analysed with table or figure. Every table or figures are followed by discussion.

CHAPTER 5

CONCLUSION

5.1 Conclusion

As a conclusion, design, development and modelling of autonomous underwater vehicle (AUV) has been presented successfully by achieved the objectives. This project focuses on the design and fabricates the AUV in mechanical as well as an electrical part with coding.

Before starting the project, gathering information and idea from other sources are very important. First, various designs of an AUV in the article were being study and get the idea to finalized design is confirmed after modification and improvement in SolidWorks. The prototype has been designed in SolidWorks CAD Drawing to illustrate the mechanical designs with the hydrodynamics shape. The algorithms for movement mechanism and depth control mechanism have been created as well. The finalized design will then undergo analysis, such as stress and strain and center of mass. The analysis on the SolidWorks helps to provide more details about the AUV when the design is tested in real situations.

Next, the project will proceed to the next stage, which is the fabrication process. This process required components that brought to assembly into the body. The assemble process have to be careful as to ensure the components are fitted in their place without any error. The depth and IMU sensor should also be tested ahead before using it. After all the components and hardware are assembled together, a few experiments are undergoing testing its performance as to achieve the objectives. Based on the balancing and buoyancy tests, AUV able to float and submerge stabilized Also, AUV's movement performance shows in the speed (0.4m/s), depth (1m) and turning (5s) tests with a few data as reference. As a result, all data collected in the experiments were considered accurate and precise.

For modelling part, depth, value data obtained from pressure sensor has been modelled in system identification to generate transfer function. The transfer function is then used in PID and FLC MATLAB for depth controller. On-Off, PID and FLC controllers can be used to tune the certain parameters to get the high performance response. However, On-Off controller takes longer time to achieve the specific desired output. The PID auto tuning shows that the tuning is quite accurate but there is overshooting occurring (5.09%). Thus, this report focused on the overshoot performance of the AUV depth controller due to AUV must be able to submerge and stop at desired depth accurately to avoid the damage from crashing to the bottom wall. Above all, stability and robustness of the AUV's depth control system can be better guaranteed by the PID original tuned response tuning than on-off and FLC control.

5.2 Future Work

In future, student can design a proper hull to hold and keep the circuit to prevent short circuit due to water leakage. This is because there is water leakage when exchange the Arduino coding and the end cap of AUV hull needed to open and close frequently. Also that can develop a left and right balancing movement for a more stable AUV. Since the position of this AUV weights are not fixed properly cause the AUV not moving in a straight line. Next, the researches for sensor include the hydrophone and sonar should be focused since AUV required better electronic parts for higher performance. In a nutshell, controller in embedded system can be designed to improve the robustness and stability of the prototype. For example, besides fuzzy logic controller, artificial neural network can be introduced into the current depth control algorithm. As a future work, the proposed methods can be more accurate through more real time experiments.

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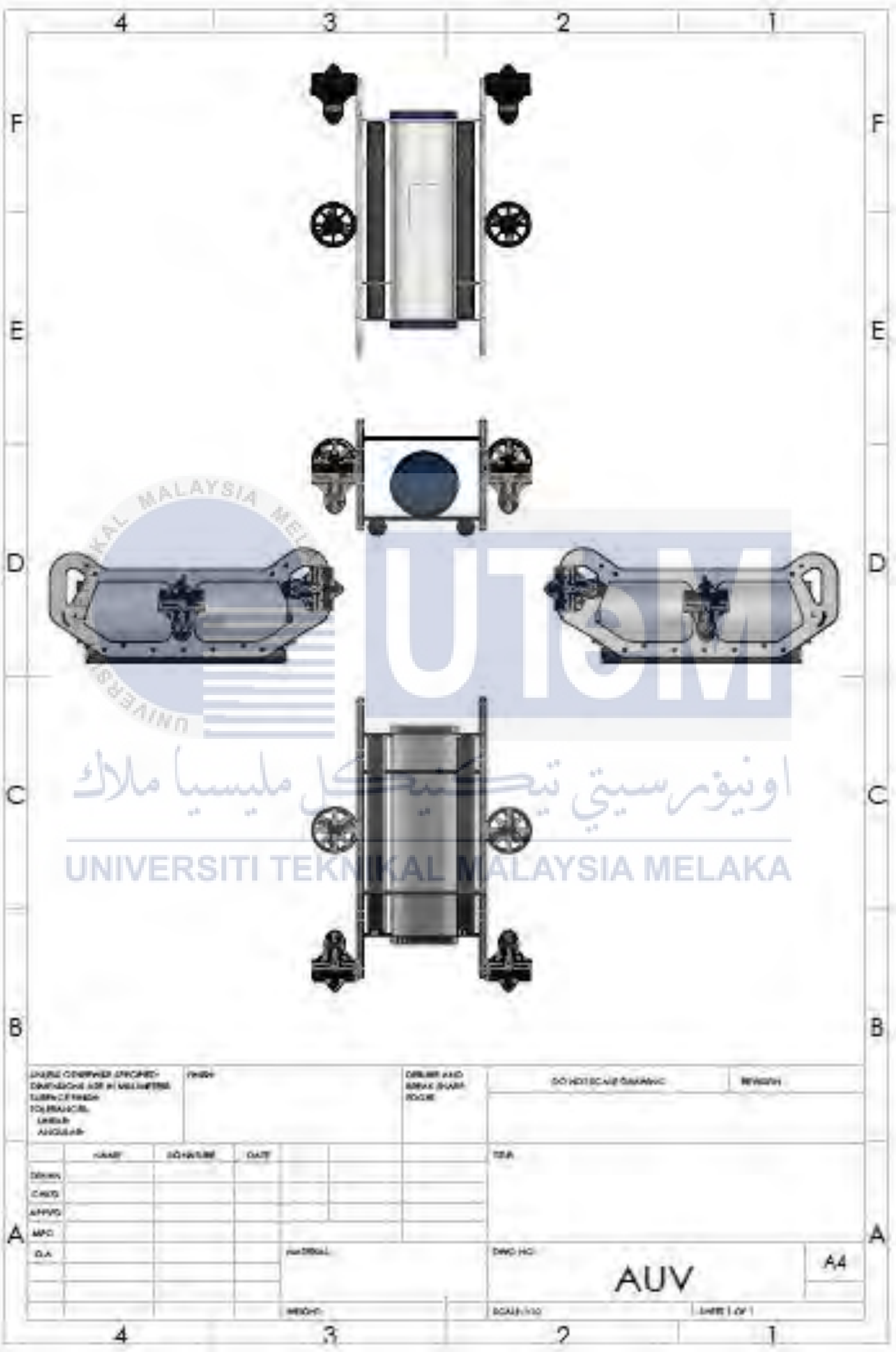
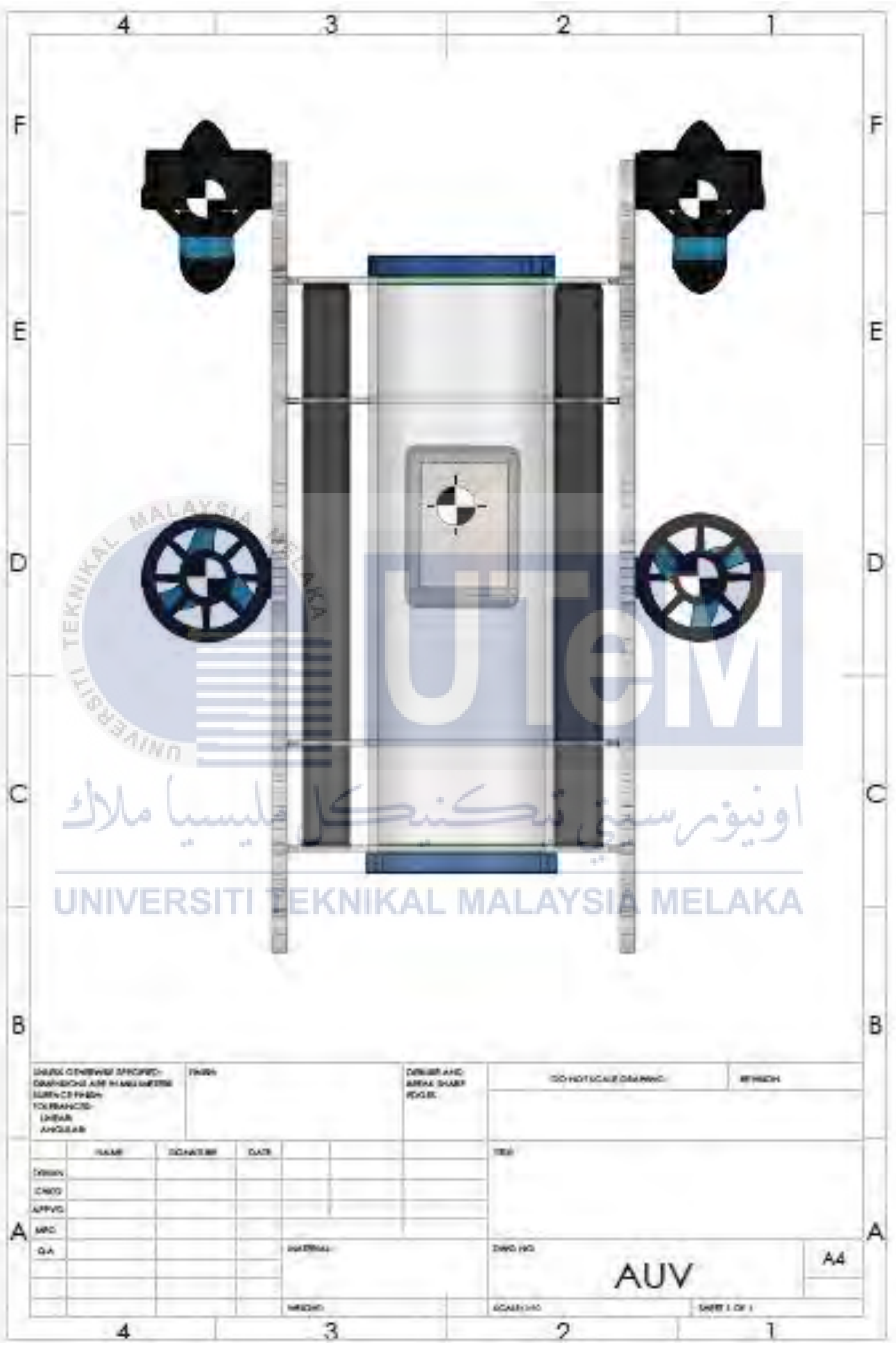
APPENDIX A: Properties of UTeM AUV TUAH

Name	TUAH
Dimension	70cm X 50cm X 30cm
Weight	18Kg
Speed	0.4 m/s (25% of full speed)
Depth	3 meters (Limitation of swimming pool depth)
Mechanical parts	Acrylic frame, PVC hull, Tupperware box, BlueRobotics thruster T-200, Iron steel weight.
Electrical parts	Battery, Arduino Mega 2560, 10 DOF IMU, MPX5700AP, Afro ESC 30A.

APPENDIX B: Solidwork View of AUV Assembly



APPENDIX C: COM View of AUV Assembly



APPENDIX D: Types of AUV

Table 1. AUVs suitable for fish-survey work.

Name	Manufacturer	Size length× diameter (m)	Weight (kg)	Speed (m/s)	Maximum range (km)	Maximum depth (m)	Power source	Sensor payload
ALTEX	Monterey Bay Aquarium Research Institute (MBARI) USA	5.5 × 0.53	–	–	1000	4500	Aluminium oxygen fuel cell	–
ARCS	International Submarine Engineering Ltd (ISE) Canada	6.4 × 0.686	1361	2	235	305	Aluminium oxygen fuel cell	–
AUTOSUB	Southampton Oceanography Centre (SOC) UK	6.8 × 0.9	2200	1.8	750	1600	Manganese alkaline 1° batteries	1, 2, 3, 4, 5
SS7 AUTOSUB	Subsea7 UK	6.8 × 0.9	2400	1.8	800	3000	Lithium ion 2° batteries	3, 4, 6, 8
DELPHINI	Bluefin Robotics Inc, USA and Thales Survey Ltd UK	3.4 × 0.53	400	1.5	111	3000	Silver zinc	–
EXPLORER 5000	International Submarine Engineering Ltd (ISE) Canada	6 × 1.15	3350	2.5	430	5000	Silver zinc 2° batteries	1, 3, 4, 6, 7
GAVIA	Hafmynd Iceland	1.7 × 0.2	50	2	40	2000	Different battery options	1, 2, 6, 8
HUGIN	Kongsberg Simrad A/S Norway C&C Technologies USA	5.35 × 1		2		3000	Aluminium oxygen fuel cell	1, 3, 4, 5, 6, 7
MARIDAN 600	Maridan A/S Norway	4.5 × 2.0 × 0.6	1700	3.5 max	24 h max	600	Manganese alkaline 1° batteries	3, 4, 6
MUST	Lockheed Martin, Perry Technologies USA	9 long	–	–	24 h max	610	Lead acid	1000 kg, 1500 l
OYDESSY 11c	Massachusetts Institute of Technology (MIT) USA	2.2 × 0.58	200	1.5	66	3000	Silver zinc 2° batteries	–
SEA ORACLE	Bluefin Robotics Inc, USA and Thales Survey Ltd UK	2–6 long		1.5		3000	Silver zinc upgrade path to fuel cell	3, 4, 6
THESEUS	International Submarine Engineering Ltd (ISE) Canada	10.7 × 1.27	8600	2	780	1000	Silver zinc 2° batteries	550 kg dry 1920 kg wet
TYPHLONUS	Institute of Marine Technology Problems Russia	3.5 × 0.8	900	2	230	2000	–	–
URASHIMA	Japanese Marine Science and Technology Centre (JAMSTEC)	9.7 × 1.5	1350	1.5	300	3500	Lithium ion	6, 8, 9

This list is restricted to vehicles which have either been directed at fisheries surveys (e.g. *Autosub* and *Gavia*) or meet the following criteria considered desirable for the task: range >100 km; depth >100 m; sensor payload >30 kg wet; truly autonomous (i.e. able to run unescorted missions without acoustic tethers or baseline beacons); non-military vehicles. Sensor payload key: 1 = CTD; 2 = ADCP; 3 = sub-bottom profiler; 4 = multi-beam sonar; 5 = scientific echosounder; 6 = sidescan sonar; 7 = magnetometer; 8 = camera; 9 = water sampler.

APPENDIX E: Safety Factor for pressure hull under 65150 kPa

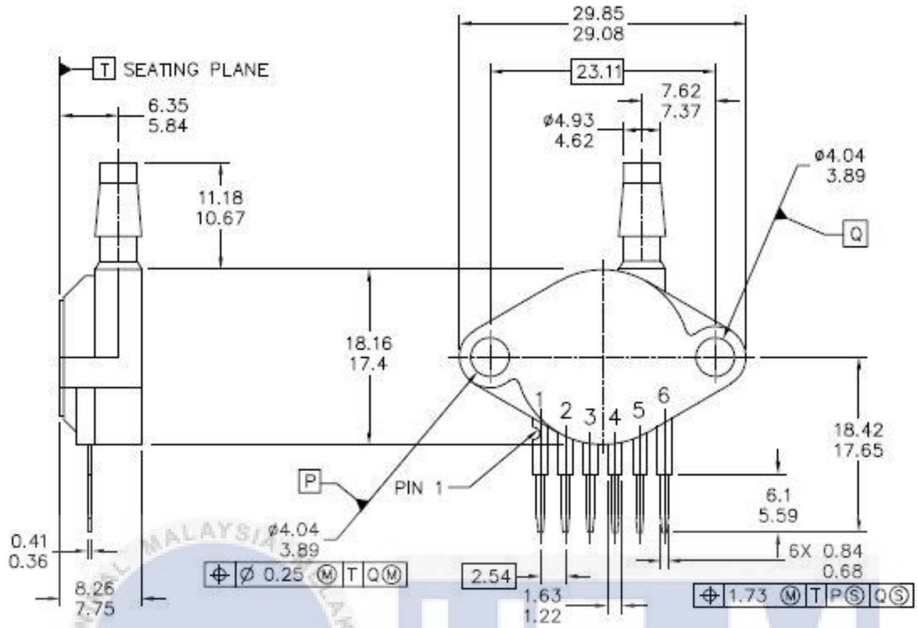
Water depth = 3215m

Water pressure = 65150 kPa

Maximum Stress = 75579.7 kPa

Blue colour indicates under safety condition; Red colour indicates material start to break.

APPENDIX F: Package Dimension for MPX5700AP

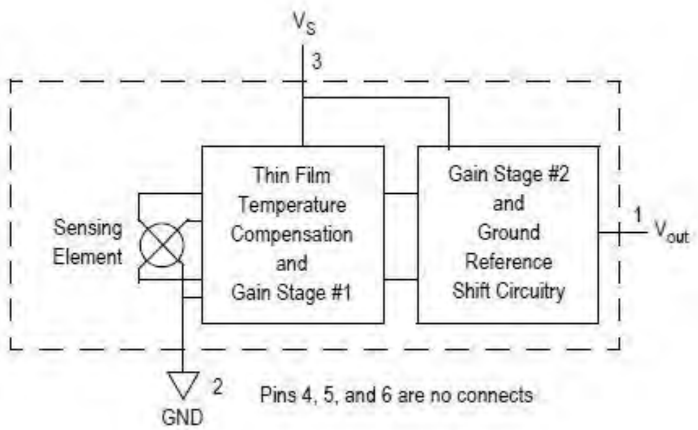


NOTES:

1. DIMENSIONS ARE IN MILLIMETERS.
2. DIMENSIONS AND TOLERANCES PER ASME Y14.5M–1994.
3. 867B–01 THRU –3 OBSOLETE, NEW STANDARD 867B–04.

STYLE 1:

PIN 1: V OUT
2: GROUND
3: VCC
4: V1
5: V2
6: V EX



APPENDIX G: Arduino Coding for Depth Control

```
#include <Servo.h>
Servo servo1;
Servo servo2;
Servo servo3;
Servo servo4;
void setup() {
 Serial.begin(115200);
 servo1.attach(9);
 servo2.attach(10);
 servo3.attach(11);
 servo4.attach(12);
 delay(1000); }
void loop() {
 float voltage = analogRead(A1);
 float pressure=((voltage/1024.0)-0.04)/0.0000012858;
 Serial.println(pressure);
 delay(10);
 Serial.println(voltage);
 delay(10);
 if (voltage <= 175) {
  Serial.println("SUBMERGE DOWN");
  servo1.writeMicroseconds(1500); // Send signal to ESC.
  servo2.writeMicroseconds(1500); // Send signal to ESC.
  servo3.writeMicroseconds(1600); // Send signal to ESC.
  servo4.writeMicroseconds(1600); // Send signal to ESC.
  delay(1000);
  servo1.writeMicroseconds(1500); // Send signal to ESC.
  servo2.writeMicroseconds(1500); // Send signal to ESC.
```

```
  servo3.writeMicroseconds(1500); // Send signal to ESC.
  servo4.writeMicroseconds(1500); // Send signal to ESC
  delay(50);   }
else if (voltage > 175 && voltage < 181) {
  Serial.println("FORWARD");
  servo1.writeMicroseconds(1600); // Send signal to ESC.
  servo2.writeMicroseconds(1600); // Send signal to ESC.
  servo3.writeMicroseconds(1500); // Send signal to ESC.
  servo4.writeMicroseconds(1500); // Send signal to ESC
  delay(1000);
  servo1.writeMicroseconds(1500); // Send signal to ESC.
  servo2.writeMicroseconds(1500); // Send signal to ESC.
  servo3.writeMicroseconds(1500); // Send signal to ESC.
  servo4.writeMicroseconds(1500); // Send signal to ESC
  delay(50);   }
else if (voltage > 181)  {
  Serial.println("FLOAT UP");
  servo1.writeMicroseconds(1500); // Send signal to ESC.
  servo2.writeMicroseconds(1500); // Send signal to ESC.
  servo3.writeMicroseconds(1400); // Send signal to ESC.
  servo4.writeMicroseconds(1400); // Send signal to ESC
  delay(1000);
  servo1.writeMicroseconds(1500); // Send signal to ESC.
  servo2.writeMicroseconds(1500); // Send signal to ESC.
  servo3.writeMicroseconds(1500); // Send signal to ESC.
  servo4.writeMicroseconds(1500); // Send signal to ESC
  delay(50); }
  }
```

APPENDIX H: Gantt chart