DESIGN AND DEVELOPMENT OF AN AUTONOMOUS UNDERWATER VEHICLE (AUV)

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

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"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 complied the partial fulfillment for awarding the degree of Bachelor of Mechatronics Engineering.

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Date : ....

I declare that this report entitles "**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 the candidature of any other degree.

Signature : ....

Name : KHOR LI ZHE

Date : ....

To my beloved mother and father

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ABSTRACT

In the 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. AUVs had upgraded their technology abilities which able to explore in deep seas. In Malaysia, the studies of the underwater vehicle are still far behind compared to western countries by referring to the case plane crashed MH370. This tragedy motivated the development of underwater research project especially AUV. One of the problems facing AUV which is the depth control and navigation system 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 and high-performance AUV with its depth control. In designing the AUV, Solidworks software is used and then the design of AUV undergoes various simulation tests such as stress, strain and displacement test. Next, the hardware that discussed and selected included frame, hull, enclosure box, propulsion and submersion that achieve a certain performance in terms of reliability and controllability. This project uses pressure sensor as depth control to determine the depth of AUV submerge. AUV uses thruster to move it along a vertical and horizontal axis that automatically operate based on the programming coding. In this project, the scope of the study focused on the mechanical design with the size (42.25cm X 55.48cm X 42.56) cm that waterproof and the submerge range of depth about 3 meters.

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. AUV telah menaiktarafkan kebolehan teknologi mereka yang dapat meneroka ke dalam laut. Di Malaysia, kajian kenderaan dalam air masih jauh ketinggalan berbanding dengan negara-negara Barat dengan merujuk kepada pesawat MH370 yang terhempas. Tragedi ini mendorong pembangunan untuk projek penyelidikan dalam air terutama AUV. 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 dengan kos rendah dan berprestasi tinggi dengan kawalan kedalaman. Dalam mereka AUV, perisian Solidworks digunakan dan kemudian menjalankan pelbagai ujian simulasi terhadap AUV seperti ujian tekanan and ujian anjakan. 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 untuk kawalan kedalaman bagi menentukan kedalaman AUV semasa menyelam. AUV menggunakan penujah untuk bergerak sepanjang paksi menegak dan mendatar yang automatik beroperasi berdasarkan pengaturcaraan. Dalam projek ini, skop kajian memberi tumpuan kepada reka bentuk mekanikal dengan saiz (42.25cm X 55.48cm X 42.56 cm) yang berkalis air dan kedalaman sebanyak 3 meter.

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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
WHOI	-	Woods Hole Oceanographic Institute
USM	-	Universiti Sains Malaysia
IMU	-	Inertial Measurement Unit
COM	-	Center of Mass
PVC	-	Polyvinyl Chloride
HDPE	-	High-density polyethylene
ESC	-	Electronic speed controller
PLA	-	Poly Lactic Acid
VON	-	Von Mises Stress

CHAPTER 1

INTRODUCTION

1.1 Introduction

Robotic submarine such as Unmanned Underwater Vehicles (UUV) has been designed and developed for the past few decades in various country and now UUVs have received the attention from Malaysia in underwater technologies. Fundamentally, it can be ordered into two sorts which is Remotely Worked Vehicle (ROV) and Autonomous Underwater Vehicle (AUV). AUV is an augmentation of the ROV's innovation, whereby ROV is guided by a human from the surface of water by utilizing the controller. On the other hand, AUV is controlled by its onboard controller guided by built-in pre-programmed command. This research is very challenging as the AUV must able to navigate and complete the task given without a human driver and remain no destruction. AUV design and commonly in torpedo-like geometry that will allow the streamlined flow [1] of water across the AUV body during underwater operation. This vehicle will have the ability to pitch vertically down itself with a depth control system by using a pressure sensor. This vehicle has thrusters for longitudinal direction propulsion like surge, sway and yaw control, some other thruster will do the heave control which is "vertical" force to move along the depth direction. Figure 1.1 shows the classification of UUV, which consist of AUV and ROV.

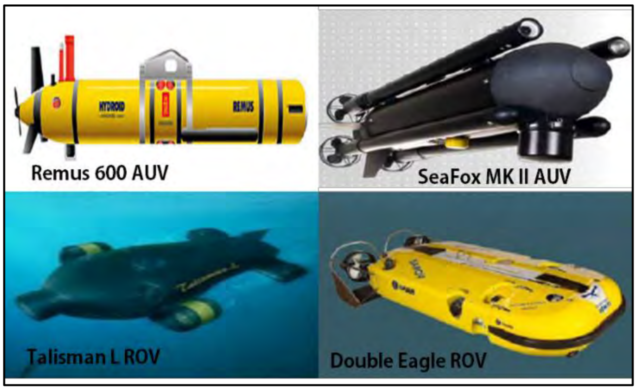


Figure 1.1: Types of Unmanned Underwater Vehicle [1]

This project is getting more and more important that shows the design implementation of an AUV for a multiplicity of research testbed platform in underwater technologies [2]. 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 size, the lightweight and the high maneuverability of this AUV are most important features that can make small AUV more suitable in shallow water to perform given tasks [3]. BlueROV is one of the remotely operated underwater vehicles from Blue Robotics product and consist of frame, watertight enclosure, thrusters, and speed controllers. This ROV is great when converting into AUV which is without human piloted.

This project focuses on converting a BlueROV mechanical design into an AUV design. Development of autonomous vehicle required an onboard computer and doing the task base on the command that set in programming. Furthermore, a depth controller for AUV and navigation controller also needs to be integrated into the vehicle. This ROV-AUV conversion needs to be held in Underwater Technology Research Lab at Ute for experimental test and fabrication purposes. Developing an AUV need a mechanical body construction by using Solidwork software for further 3D fabrication, and construct an electrical and electronic circuit design, and follow by 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. However, the outcome of this project should be a small, highly transportable and low-cost AUV, constructed to participate in AUV competitions and to provide a platform for future research. For purposes of economy, it is based on a former BlueROV, which was the product of BlueRobotics. Following modifications and conversion, navigation and depth sensor implementation, as well as motion control with the help of actuators controlled by onboard controller make the vehicle able to perform mission tasks autonomously. The conversion of this ROV to AUV is the first project constructed in this lab. The project is to save the cost by developing a new AUV. The conversion will add more features to the vehicle with direction drag minimize, design in symmetry, optimized thruster positioning, stability and optimizing AUV performance [4].

Next, by referring to plane crashed case, MH370 which crash into the Indian Ocean. Malaysia needs to use technology from Australian country due to lack of technologies to detect splinter of the plane. Malaysia required paying the commercial aid to relevant countries, while they actually used this chance to continue their further research [5]. Thus, the consequence of this project develops an AUV with highly transportable, small size and low-cost AUV to join in any AUV competitions like Malaysia AUV Challenge, Singapore AUV Challenge and Innovate. The project starts with design and fabricates following modifications, the addition of basic sensor and common movement control.

1.3 Problem statement

Designing and developed an 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. AUVs are now being used for a variety of tasks, including oceanographic surveys, demining, and bathymetric data collection in marine and riverine environments. Accurate navigation is essential to ensure the accuracy of the gathered data for these applications. Underwater communications are low bandwidth and unreliable, and there is no access to a global positioning system. Past approaches to solving the AUV localization problem have employed expensive inertial sensors, used installed beacons in the region of interest, or required periodic surfacing of the AUV [6]. While these methods are very expensive and large scale vehicle.

Motion control of AUV is very important because this may cause underwater vehicle loss during surveillance because autonomously navigate in the underwater seabed which is unpredictable and inherently dangerous. In motion control which includes heave, sway, surge and yaw of an AUV are particularly dangerous in horizontal and vertical trajectory due to easier get inspected structure damage by crashing to the stone and bottom of the seabed. Thus, this project is developing to solve by improving the current AUV performance in terms of motion control and efficiency.

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 a 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 the Indian Ocean should be a warning to everyone about the importance of improving the technology in Malaysia [5].

1.4 Objective

Three objectives that required to achieved during this FYP

1. To design and develop of Autonomous Underwater Vehicle (AUV) and based on Remotely Operated Vehicle (BlueROV).
2. To integrate the depth sensor and IMU sensor into AUV to follows the desired set point.
3. To investigate the performances of AUV in terms of speed.

1.5 Scope

a) Less than 70 cm × 50 cm × 50 cm and the weight is less than 40 kg in air.
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 limited depth of a swimming pool.
g) The maximum duration of the AUV activity in underwater is 1 hour per cycle to prevent humidity hazards.
h) The electronic parts used are microcontroller Arduino UNO, pressure sensor MPX5700AP, GY-80 IMU sensor and speed controller (ESC)
i) GY-80 IMU sensor is used as input for the one-axis tilt balancing mechanism of the AUV.

1.6 Organization of Report

Chapter 1 is the introduction and some motivation of the project. The introduction is to overview some basic operation of an underwater vehicle and the different between ROV and AUV. Thus motivation is based on current problem statement that needs to be solved.

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 was chosen that were developed. There are comparisons between the shape and materials of mechanical parts.

Chapter 4 are results and discussion that described several in the SolidWorks to help fabricate the AUV's parts. 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.

In Chapter 5, conclusion for the entire progress for this project. There are additionally a few proposals for future work and suggestions for the coming semester.

1.7 Summary

AUV is a very important water application that will give a lot of benefits. Conversion of ROV in UTeM Underwater Lab is very important for the previous designed ROV to become a new technology AUV. It summarized that the AUV platform is very limited in Malaysia because the requirement component specification is very critical like a 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

Autonomous Underwater Vehicle are generally battery powered and convey its own particular computer. This locally available computer is the necessity for their self-governing conduct. They pick up data from their sensors for route and mission assignments. The Autonomous Underwater Vehicle advancement started in the 1960s at the College of Washington and made substantial jumps in the mid-1990s with the sponsorship of Massachusetts Establishment of Innovation (MIT) and the Workplace of Maritime Exploration (ONR). The MIT AUV Lab created the AUV which could be complete numerous underwater missions. MIT has now developed the Odyssey IV which is the latest iteration of AUV in MIT. Another institute which is Woods Hole Oceanographic Institute (WHOI) also played important roles in design and development AUV. Their fleet of AUVs are the cutting edge of underwater autonomy and with the worldwide capability WHOI has, their work is some of the most highly respected oceanographic research in the world. This important research drives AUV development forward every year and with more advanced technologies and features.

AUVs have numerous purposes. Most involve research but others can involve search and rescues, object identification, water sampling, mapping, communication, and control research. AUVs can go places where is to too dangerous or expensive for humans to go. They can take numerous samples for research without human interaction. Although AUVs are expensive pieces of hardware, the information they gather can be invaluable.

2.2 Theories and Principle Apply

There are several theories and principles are required to discuss during AUV design processes like density, the center of gravity, buoyancy, stability, hydrostatic pressure, and mass of the vehicle. 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 to an object (kilograms, Kg) whereas Volume is the quantity of space taken up by a quantity of matter (cubic meters,m^3). Basically, density can be used to define or determine the substance. This is important to relate the type of material use and its density. As all the parameters in the model are based on the physical parameters of the motor, propeller, and fluid density (***p*** = 1000 kg/m3) need to consider [7]. By knowing the density of the material use and we can select the best and suitable material for AUV. Density control is very important to allow AUV in good depth control and motion control. Figure 2.0 shows the difference between different materials.

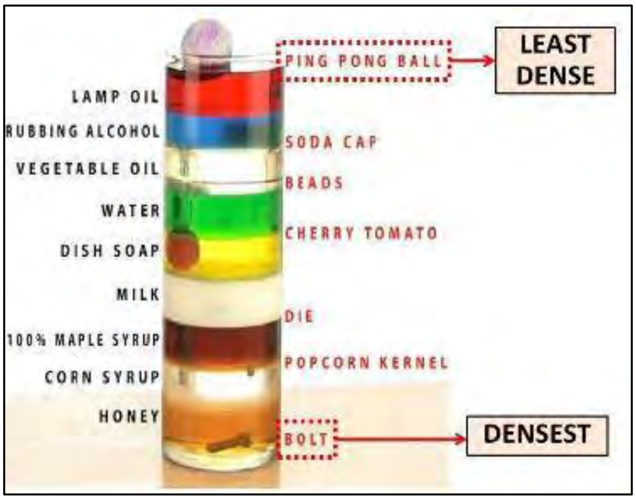


Figure 2.1: Density of different material [7]

2.2.2 Center of Mass

Center of mass is defined as the mass-weighted average of the positions of particles and the center of mass is a statement of the spatial arrangement of mass. Basically, the center of mass is the distribution of mass in a particular object. For the underwater vehicle is very important to have an accurate center of mass this is because of differential actuation is obtained by making the propellers of each pair of motors, horizontals, and verticals, actuate with different forces to obtain torques about the center of mass [3]. Center of mass will easily affect when designing a manipulator to the body of AUV. Thus the stability and balancing of the vehicle are depending on the center of mass of the whole structure design of the AUV. Figure 2.1 shows the plump line method to draw center of mass.

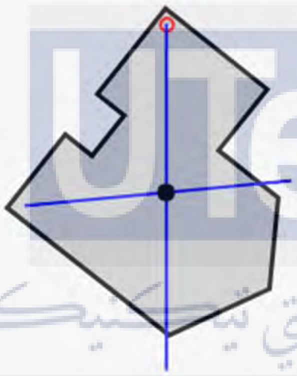


Figure 2.2: Plump line method

2.2.3 Buoyancy

Buoyancy or Buoyant force is a natural phenomenon that occurs according to Pascal's Principle. This principle states that the pressure is a function of the static fluid pressure which is dependent on the vertical location at which the pressure occurs. According to 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 another word, an AUV is submerged in 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 [8].

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 place as shown in Figure 2.2.

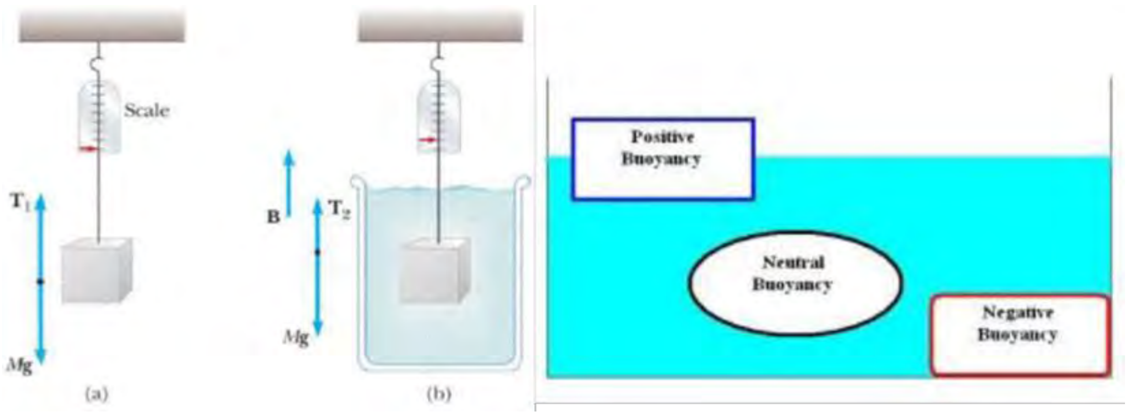


Figure 2.3: The buoyancy principle [8]

Take the example of a ball of constant material and perfectly spherical. When this pass is placed into a body of water, the top of the ball will experience a different pressure that the bottom of the ball. The vertical location of the top and bottom of the ball relative to the surface will cause the unequal application of pressure to the surface of the ball, creating a buoyancy force in the positive y-direction. If the buoyant force in the positive y direction is able to overcome the weight force in the negative y-direction, the ball will float upward, demonstrating the effects of buoyancy [9].

The water level in the onboard ballast tanks is typically manually set for neutral buoyancy before each mission, while the vehicle is on the surface. The ballast tank contents are not normally adjusted to control vehicle depth and orientation while the AUV is in operation. As a result, vehicle trajectory and orientation are exclusively controlled using the vehicle's control surfaces during a mission. The challenges with controlling the depth and trim of an underwater vehicle include nonlinear hydrodynamic forces [10]. Ballast tank of an AUV 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.

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 2.3. 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.

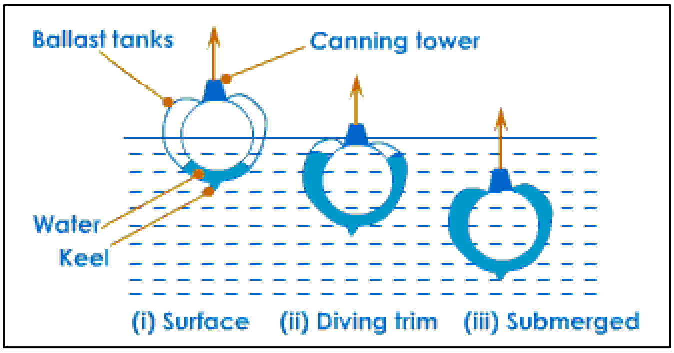


Figure 2.4: The operation of ballast tank [7]

2.2.4 Stability

Underwater vehicle 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, the center of buoyancy and metacenter of pitchers. Initially assume that there is no water flows, the centers of mass and buoyancy affected the stability of a static body underwater [8].

For a dynamic underwater body, to increase dynamic stability, the Center of Mass should be associated with 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 2.2.4

2.2.5 Hydrostatic Pressure

The water depth to pressure ratio is important to understand for design constraints and material selections for a robotic system. 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.

The relationship of water depth to pressure is a linear relationship where pressure increases as depth increases [11]. The atmospheric pressure at sea-level is 14.7 pounds per square inch absolute (psi). To keep things simple, this has been given a unit of 1 atmosphere or ATM. Pressure increases at a higher rate in water than air due to the higher density of water. Specifically, water pressure increases 1 atmospheric pressure or 14.7 psi every 33 feet (10.06 meters) below the surface of the water [11] [12]. Underwater vehicles must operate in the safety depth range to avoid the high pressure on the underwater vehicle during the operation. Once a depth range is determined, all materials selected must be able to withstand the pressure at the give operating depth.

AUV depth submerges can determine the pressure value and this formula. According to Pascal's law, the consequential hydrostatic pressure is isotropic and acts in all directions equally [7].

Pascal law states that ($p = \rho g h$) (2.1)

Where p = water pressure

ρ = water density

g = gravity force

h = water depth

2.2.6 Environmental Force

Natural waves and wind blow on the sea surface influence consider as environmental disturbances. The underwater vehicle such as the AUV will get disturbed in the form of stability and motion. Besides that, the unstable temperature under the deep sea will risky the AUV electronic parts. Unstable temperature able causing water in the hermetically closed inside of the AUV and mostly spoilt the electronic devices.

2.3 Mechanical Design

The mechanical subsystem consists of the pressure hull design, AUV frame, electronics enclosure box, and the propulsion system. At this stage, the dimension configuration, mass and weight, material selection, electronic device installation and others required to be considered due to the performance of AUV when underwater operation.

2.3.1 Pressure Hull design

An Autonomous Underwater Vehicle hull must be able to protect electrical components from water and provide a watertight environment. The design of hull should able to prevent water from a leak in and server as the housing for all non-waterproof component. Hollow design and a watertight compartment will be used to enclose all electrical components and batteries that are used to drive the vehicle. This compartment is sealed off using two sealing caps that are attached to the ends of the central cylinder. They are designed in such way that the electrical components and batteries can be accessed with ease, simply by removing one of these sealing caps and withdrawing the board on which all these components are placed. Though, the AUV will incorporate a waterproof plug with easy access to loading batteries [3].

The hull must be light and strong, high durability and corrosion resistant as it will be submerged in a saltwater environment as Figure 2.4. 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.

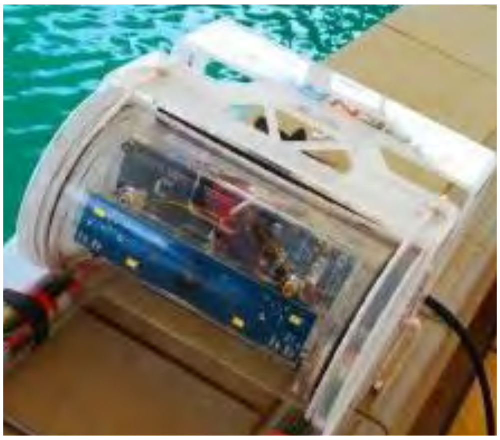


Figure 2.5: PVC Pressure hull [13]

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.

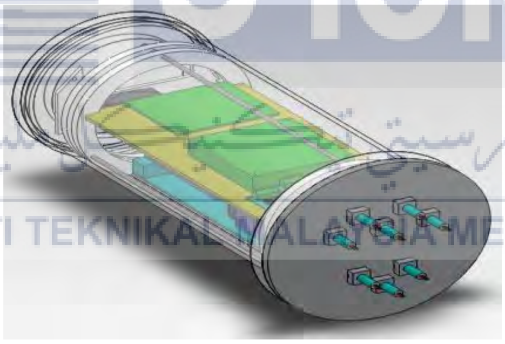


Figure 2.6: Pressure Hull design with 2 caps [14]

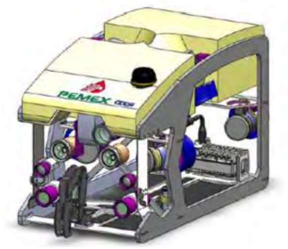
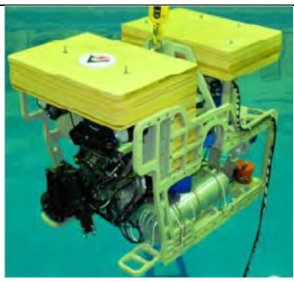
2.3.2 Architecture Design of Frame Structure

The structural of vehicle frame is the main support of the underwater vehicle. This support is to maintain normal operation in a different type of motion control. These are made of POM plastic, crafted in a linear finish, and are fastened using a screw on the exterior face of either end-cap. Their primary function is to enable the rest of the exterior modules and components of the AUV to be fixed to the central cylinder.

There are two major frames for an underwater vehicle, which is open frame and close frame. Basically, closed frame UUV 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 a large amount of internally mounted thrusters. Two common designs for AUV drawings which are open frame and close frame as shown in Table 2.1 and Table 2.2. Vehicles with high aspect ratio used for long moving distances and vice versa. There are advantages and limitation of each type of design. However, the shape of the vehicle depends on the purpose and application of 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 closed frame design. The following part shows about these two types of AUV include open frame (PEMEX ROV, MARMA ROV, UTeM ROV, USM AUV, Robbe 131, P2-ROV) and close frame (UTeM AUV, Bluefin SandShark micro-AUV, Tri-TON 2, X4-ROV, ODIN and URAS HIMA).

Table 2.1: Comparison table Architecture design of Open Frame Underwater Vehicle

Name	Manufacturer	Architecture	Description
PEMEX ROV [15]	CIDESI, MEXICO		i. 1.4 m x 0.9 m x 1.2m (350 kg) ii. 6 thrusters iii. Maximum operation depth: 2,000 meters iv. Depth sensor, Compass Altimeter, Rate Gyros and Sonar
MARMA ROV [16]	TUBITAK, TURKEY		i. The frame is made from polypropylene. ii. 3 phase 440VAC and single phase 240VDC input iii. 5 DOF (surge, sway, yaw, heave, roll) iv. Aluminum pressure hull v. Ultra Short Base Line (USBL) system

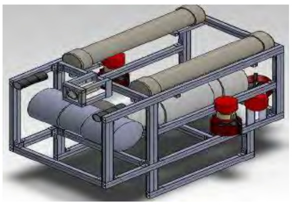
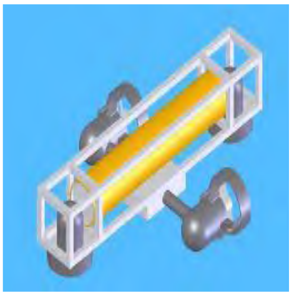
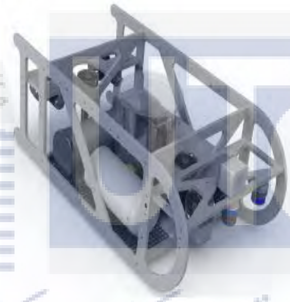
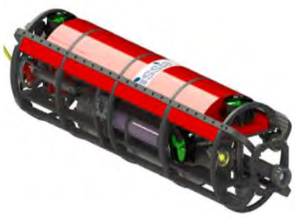
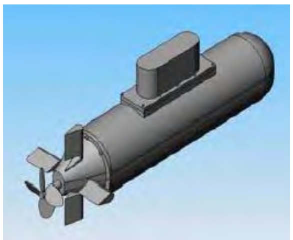
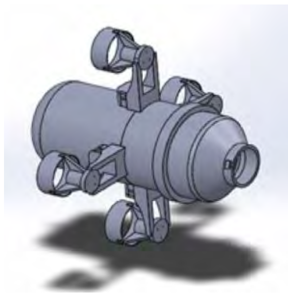
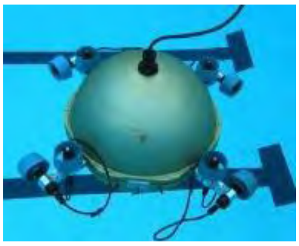
UTeM Smart ROV 1 [17]	UTeM		i. 300mmX 600mm X 450mm ii. 4 thrusters (vertical and horizontal vector 45º) iii. Aluminium frame with a vision system and ballast tank iv. Cylinder PVC pipe pressure hull v. Depth and IMU sensor
USM AUV [18]	USM		i. 1m long and 0.5m width (30kg) ii. Sensor fusion and actuator control iii. 4 thrusters (2 vertical, 2 horizontal) iv. Depth and Gyro sensor v. The full state with a feedback controller
Robbe 131 [19]	Team TomKyle		i. The frame is made from polyethylene (PE) ii. 5 thrusters (2 vertical, 3 horizontal) iii. Pressure hull made from polyoxymethylene (POM) iv. 2 LiPo Ion batteries packs v. Sonar sensor, IDS UI-1241LE-C-HQ camera, Keller 33x pressure sensor, PCB sensor vi. Kontron KTQM67 embedded motherboard
P2-ROV [20]	ISSIA, Italy		i. Torpedo shape 34cm x 34cm x 140cm (40 kg) ii. Easily transported by hand by two operators iii. 6 DOF with 5 thrusters iv. 1 bow thruster for maneuvering, 2 thruster for horizontal motion, 2 thrusters for heave motion v. Stainless steel cylindrical canister for electronic parts

Table 2.2 Comparison table Architecture design of Close Frame AUV

Name	Manufacturer	Architecture	Description
UTeM AUV [21]	UTeM		i. Skeletal frame is made from aluminium ii. 2 cylindrical hulls iii. 4 motors fin propeller and wing iv. Tank with float lever switch v. DC motor and Servo motor
Bluefin SandShark micro-AUV [22]	Bluefin Robotics		i. 200 meters depth limit ii. Hull diameter of 12.4cm, length 103.54cm (4.9kg) iii. Torpedo shape iv. The vehicle is ballasted positively buoyant v. 24 Volt bus power supply vi. DC Brushless Motor vii. speeds of approximately 2.5 meters per second
Tri-TON 2 [23]	University Tokyo		i. 1.4m x 1.5m x 0.8m (260kg) ii. 3 pressure hulls iii. 4 DOF with 5 thrusters iv. Maximum speed 0.6m/s v. Maximum depth 2000 m vi. 4 Li-Ion 26v 30Ah vii. Sensor DPT6000 depth sensor
X4-ROV [13]	UMP		i. Torpedo hull shape made from PVC pipe ii. Four thrusters arranged vertically and horizontally to control the position by itself iii. 6 DOF iv. Stream HD video to a laptop v. Maximum depth 100m

ODIN [24]	Autonomous System Lab		i. 0.64m diameter sphere made of aluminium AL6061 ii. 123.8kg and 1.3 N positive buoyant and 100m depth rated iii. 8 Tecnadyne brushless thrusters via four fabricated mounts
URAS HIMA [25]	Mitsubishi Heavy Industry		i. 10m x 1m x 1 m (10 tons) ii. Maximum submerge depth 3.5km iii. Crushing range 300km iv. PEFC fuel cell or Li-Ion rechargeable battery v. Side scan sonar, video camera, sub-bottom profiler, multi-beam echo sounder vi. Oil bladder for buoyancy

2.3.3 AUV Electronic Enclosure Box

The concept of the electronic enclosure box is similar to hull concept only the size is different. Smaller enclose box allow all the electronic components of AUV separate from water. Generally, this electronic component cannot be open during underwater operation 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. Design of the waterproof box is needed for electronic parts like a battery, microcontroller, sensor, and camera. The cover of the box needs to be transparent because simply to detect the function inside it. Normally, a 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.

Based on the freshman project, which organizes by Polytechnic University, they have chosen Pelican 1010 case as the RCX's water-proof housing as shown in Figure 2.6. 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 watertight seal around the wires. The wire was then inserted into the case and the connector head re-attached to the wire [26].

Figure 2.7: Electronic enclosure [26]

2.3.4 Propulsion System

Taking into account the requirements for Proteus AUV [27], there are two thrusters were chosen to thrust in the horizontal thrust and four thruster use for vertical thrust. The thrusters selected were the T100 thrusters by BlueRobotics [28] (Figure 2.8) since they are an affordable solution for underwater propulsion and are able to provide the necessary forces to drive the AUV.

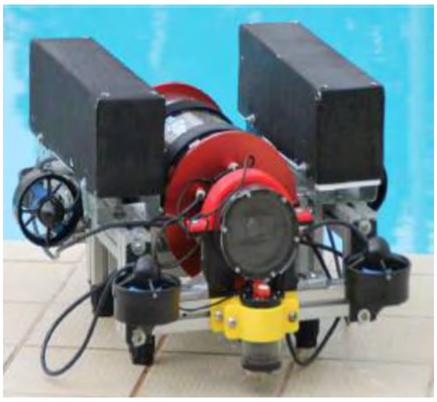


Figure 2.8: Proteus AUV [27]

Figure 2.9: T100 Thruster [28]

AUV mostly uses thrusters for propulsion due to the cost of alternative systems. The AUV degrees of freedom are controlled by the location of the motor and number of thruster used. The configuration of the thrusters is also the main factor to the degree of freedom. The force acting by the thruster can make it move in 6 DOF. 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.

2.4 AUV Coordination and Dynamics system

The translational motion of the underwater vehicle in surge forward direction and reverse direction is rather simple. However, it is very important to realize a lateral motion in heave (z) and sway (y) and surge (x) direction. The idea to achieve the motion is by vector force where the vectored thrusters are mounted at angle to create a vector thrust, Besides that, an underwater vehicle 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 a longitudinal translation. The Y-axis point moves the right-hand side direction and is a literal translation. For maintain stability if AUV in the Z-axis which is depth control must be stable. Thus, in order to keep the vehicle stable when designing AUV, it must be considered the number each DOF [29]. Figure 2.9 shown that different axis with the different dynamic motion of AUV.

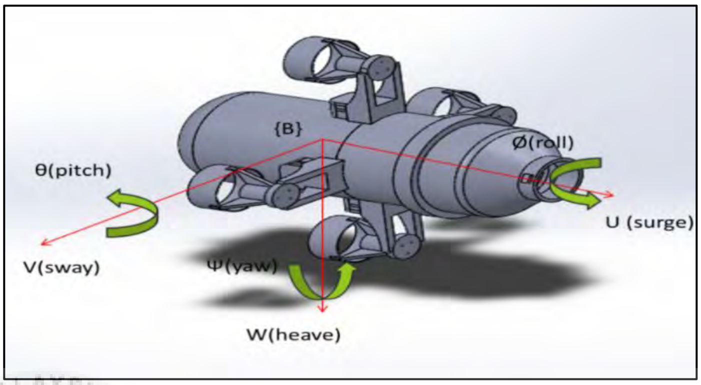


Figure 2.10: 6-DOF coordinate system [13]

Basic motion equations were derived to allow for open-loop control of the AUV. Using these equations the AUV could be controlled both autonomously and remotely. A coordinate system with the z-axis acting on the gravitational axis allows the AUV can be positioned in the water, while the equations will be simulated in an orthogonal coordinate system.

Every motion of AUV will have its force of motion and this will is according to Newton's Second Law. Every motion can be solved this way with the exception of the Z-motion. Thus is possible to derive equations for the distance in terms of time and also the acceleration of the AUV also can be calculated. By integrating the acceleration with time twice, a simple distance verse time equation achieved.

The equation showed that each motion is broken into two phases, an acceleration from zero velocity and a deceleration back to zero velocity. Using initial conditions each phase can be broken down and analyzed. In the first phase, the constants of integration would be zero. In the second phase, C1 would be the velocity at the end of the first phase, and C2 is the distance at the end of the first phase. The only difference between each motion is the acceleration.

Force Equation: F= ma

$$a = \frac{F}{m} \tag{2.2}$$

Velocity Equation: $\int a\, dt = at + c1$

$$= v \tag{2.3}$$

Distance equation: $$\int v\, dt = \frac{at^2}{2} + c1t + c2 \tag{2.4}$$

$$= x$$

2.4.1 Horizontal motion

The main horizontal thrusters mounted on the side of the AUV are able to provide horizontal motion. Firing them simultaneously will create the force necessary to propel the AUV. The first phase will have the AUV propelled either forward or backward from a stationary position. In the second phase, the thruster will be a fire in the opposite direction to slow the AUV back down to rest.

Horizontal Force Equation: $$Fx = m\frac{d^2x}{dt^2} \tag{2.5}$$

2.4.2 Pitch and Roll

Pitch is controlled by firing the two waterjet thrusters located on the bow or the stern of the AUV. The maneuver is done by turn on the thruster ones located on one side and then turn on the others located on the opposite side. Beside that roll is achieved when maneuver by two sides vertical thruster in opposite direction. Rolling should be used solely for maintaining proper orientation of the sub. The weight and buoyancy forces are called the restoring forces. These forces are responsible for bringing the vehicle back to its stable position in roll and pitch, which are defined to be zero in that position.

Pitching Moment Equation: FM$= ly\frac{dq}{dt}$ (2.6)

Rolling Moment Equation: FL$= lx\frac{dq}{dt}$ (2.7)

2.4.3 Yaw

Yaw is performed by turn on the main thrusters in opposite directions. Turn on thrusters in the horizontal direction with AUV by 45º vectored thruster configuration will provide the yaw motion with minimum drag. Thus the AUV is able to yaw in counterclockwise and clockwise yaw rotation.

Yawing Moment Equation: FN$= lz\frac{dq}{dt}$ (2.8)

2.4.4 Vertical

The vertical maneuver is to heave-thruster components. Unlike the other motions, the horizontal motion combines front and rear thruster to give the desired direction of motion. The maneuver is simple to calculate. The density of water at these depths is assumed to be constant and the pressure sensor as the depth sensor for feedback analog input for controlling AUV depth. Basically, the configuration of heave-thruster is built side by side of the hull to provide vertical upward and vertical downward motion of an AUV.

Vertical Force Equation: FZ $= m\frac{d^2z}{dt^2}$ (2.9)

2.5 Electronic Design

The 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 by any electronic issues.

2.5.1 Navigation Sensors

The pressure sensor mentioned above is also a navigation sensor since it is used to calculate depth. Additionally, the vehicle uses an Inertial Measurement Unit (IMU) to calculate its orientation and a GPS to know its absolute position when at the surface. The IMU sensor used is 9 axis Razor IMU 9 MOF 10736 IMU sensor [27]. The IMU records accelerometer, gyroscope, and magnetometer data. The IMU is very capable of providing an accurate heading while filtering out any magnetic noise which would otherwise impede the functionality of the magnetometers, thus we can estimate the orientation of the system. This device is used to obtain vehicle's position when underwater and device have a connection to the processing unit as a feedback control system.

2.5.2 Electric Power Supply

AUV is powered by using 12V DC battery 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 for supplying entire electronic component. Two pairs of batteries are supplying for thrusters and propeller whereas another two pair of batteries supplying electronic components like a sensor. They used onboard power to enable the AUV function in autonomous mode [18].

Tadahiro Hyakudome [30] proposed that lithium-ion battery is good for every component in AUV due to the surrounding high underwater pressure low-temperature situation is not suitable for those chemical reactions in underwater area. Lithium-ion (Li-Ion) battery has many merits more than other batteries as follows and Figure 2.10:

1) Energy density is very high, this is the most important factor when choosing a battery

2) Operating voltage is also high

3) No need to revitalize according to its memory

4) Safety

5) Maintenance free

6) Emits no gas when charging

7) Longer lifetime than the other batteries.

Figure 2.11: The Lithium-Ion Battery for AUV

AUV Robbe 131 designed by Team TomKyle [18] 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. Battery-protected 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 merged board to provide a single power rail for the vehicle.

2.6 Software (SolidWorks, Arduino)

SolidWorks software is an engineering design tools 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 a real environment. The designer would alter the design so that it can perform better before fabricating it. It is able to perform a 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 UNO is a microcontroller board based on the ATmega328 and is powered by 7V-12V DC input. It suits to use due to contains everything to help the microcontroller as basically interface it to a PC with a USB link or power it with an alternative current to direct current connector or battery to begin. Arduino used to receive the data signal from the sensor and then process and send back the signal to the actuator. For example, IMU sensor detect underwater vehicle is in unbalance and send the analog data to Arduino to process and for the next instruction, thus the thrusters will move to control roll direction according to the coding set by the user.

2.7 Summary

As a conclusion, it introduces a summary completed the whole mechanical, electronics and software part. It also discussed some history of AUV and ROV, hardware, the mechanical and electrical system of the underwater vehicle. By comparing both AUV and ROV, the ideas to design and develop of AUV is much clear and useful. Thus the conversion of BlueROV to AUV will become easier with the knowledge of this both underwater vehicle.

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. Beside that it gives the general idea to the reader from the initial stage to the final stage. Staring from the previous chapter which is an introduction and background of the project until the project hardware design and electronic design and now this chapter will show more about on the engineering design method and implementation steps.

Firstly, general task flowchart is incorporated into this part as appeared in Figure 3.1. It explained briefly how the project starts at 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 of 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 are 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 Flow Chart

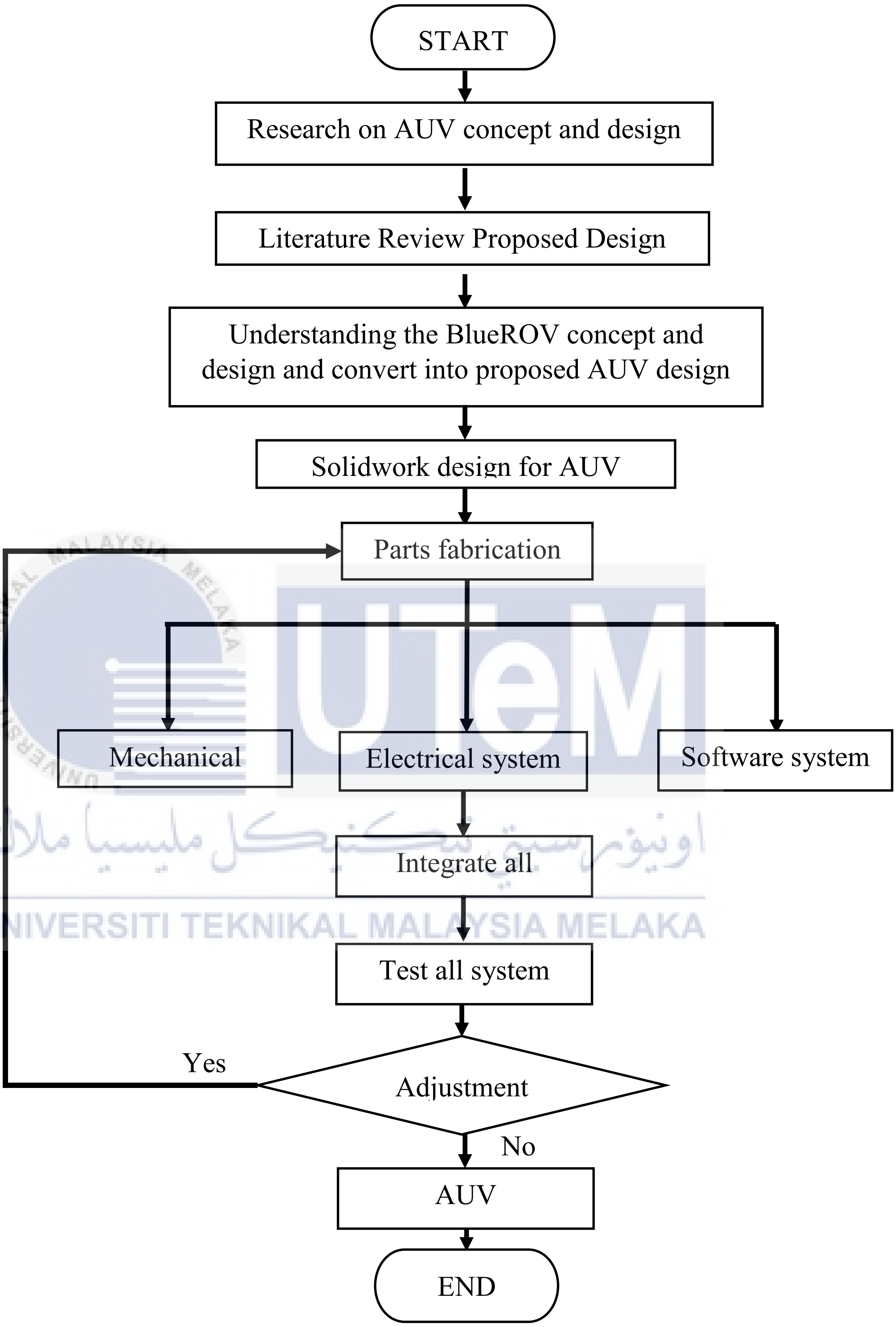


Figure 3.1: AUV project flowchart

3.3 Project Methodology Flow Chart

The structural methodology is made according to the flowchart in Figure 3.2. This will discuss the method used to complete the hardware and software design for this AUV project.

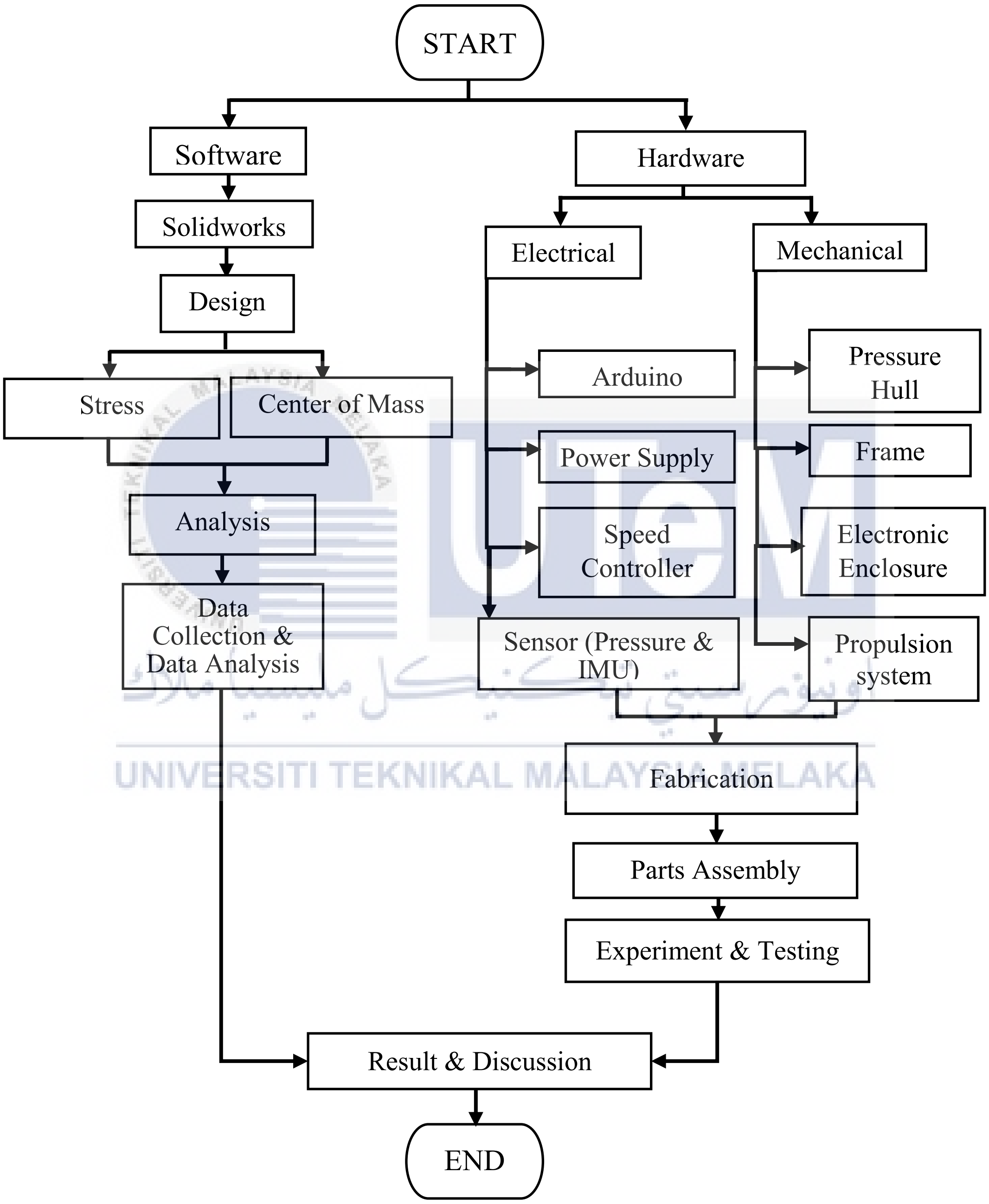


Figure 3.2: AUV Project methodology flowchart

3.4 Project K-Chart

Project K-Chart is a tool for deliberately sort out research into the extent of issues under investigation, strategy as tree chart as appeared in Figure 3.3.

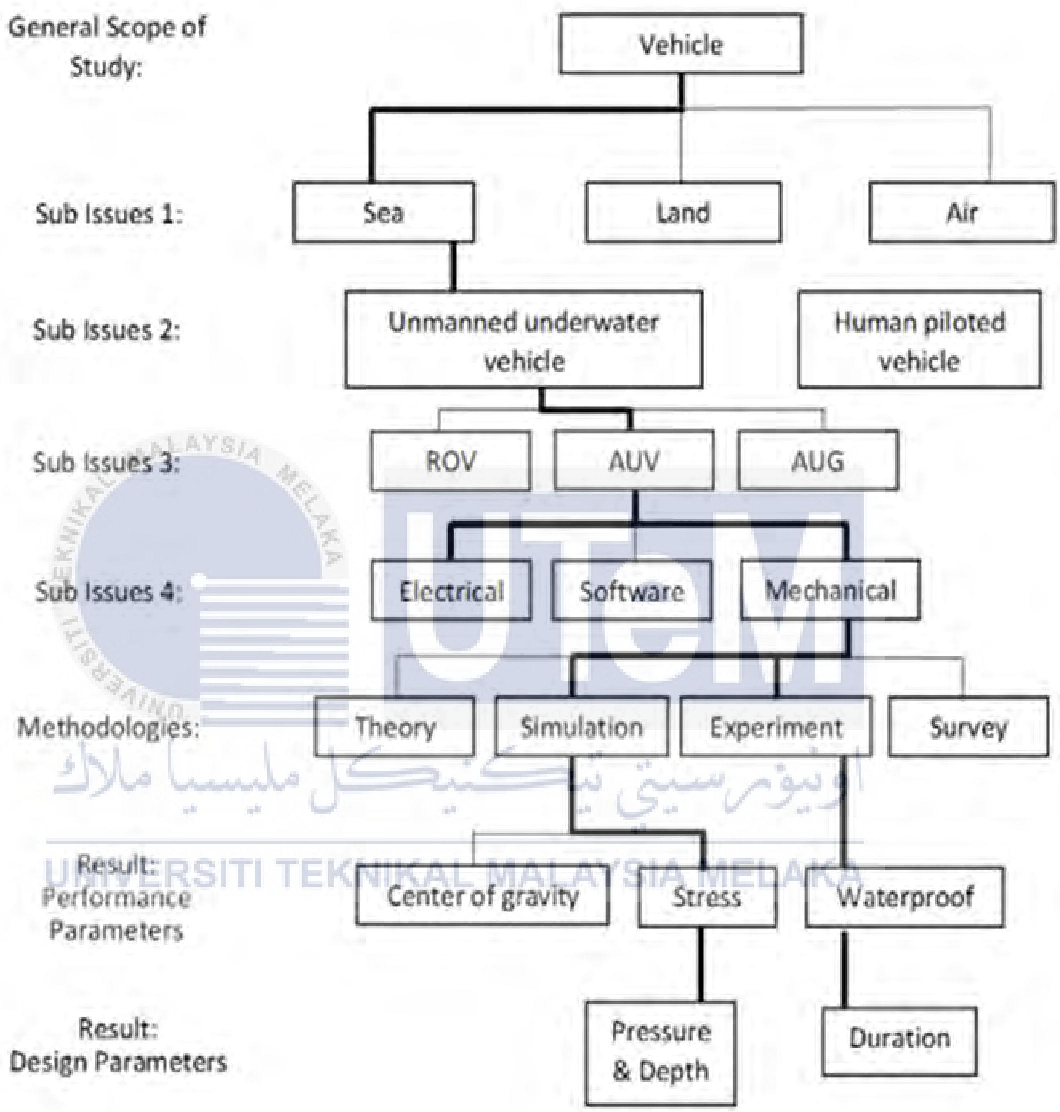


Figure 3.3: K-Chart for AUV project

3.5 Mechanical Description

3.5.1 Pressure Hull

Cylinder tube is used as a pressure hull to keep all the electronic components in the dry condition. A cast acrylic cylinder tube with 11.75-inch length, 4.5-inch outer diameter, and 4-inch inner diameter is used. Cast acrylic is in the form of transparent polymethyl methacrylate. Pressure hull is sealed by 2 interchangeable end caps and at the front and another one at the back of the tube. Both end cap of the hull enclosure mounting with an aluminium flange in order O-ring to bind on the cap tightly. This end cap consists of double O-ring that acts as the sealant for the pressure hull. Both caps with holes for cable penetrators. Figure 3.4 shows the pressure hull overview from the design of BlueRov. Table 3.0 shows the specification of the watertight pressure hull [31].

Figure 3.4: Watertight Pressure Hull [31]

Table 3.0 Specification of watertight Pressure Hull

Parameter	**Value**
Maximum Tested Depth (Saltwater)	65m depth
Maximum Pressure	637.6 kPa
Tube Inner Diameter	152.4 mm
Tube Outer Diameter	165.1 mm
Tube Thickness	6.4 mm
Acrylic End Cap thickness	12.7 mm
Aluminum End Cap Thickness	6 mm
Total Length	304.8 mm

3.5.2 AUV Body Frame

The frame is the main support of the underwater vehicle because it needs to hold all the hardware component during the AUV underwater operation. 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 changed or edit easily rather than the close frame. Normally, the close frame is designed as a submarine, fish or marine animal shape while open frame more likely ROV shape. The close frame has limited shape of the pressure hull since all the boxes or component can only keep inside the frame.

A BlueRov frame design by Blue Robotic is used as the frame for AUV. This black HDPE (High-density polyethylene) frame is selected because the frame provided flexible empty space for pressure hull and thrusters assemble. Besides that, both frames are held by 6 round aluminium rods at the surrounding of the frame and 2 black square plastic sticks at the middle of the frame. 2 black plastic sticks is to provide a platform for hull assemble and improve the stiffness of the frame structure. Figure 3.5 below shows the diagram of BlueROV frame.

Figure 3.5: BlueROV frame [32]

3.5.3 Electronic Enclosure Box

The function of pressure hull is same as electronic enclosure box, the only things are the size smaller than the pressure hull. AUV need a large capacity of DC power to operate a long time under the water. The external battery enclosure box is needed, thus a rectangular enclosure for the battery is design using Solidworks as shown in Figure 3.6. Size of the electronic enclosure is 17.5 cm long, 11.9cm width and 9.2cm height that base on the size of the battery. Furthermore, the enclosure cap of this box is also designed using Solidworks to close the battery enclosure box fully as shown in Figure 3.7. Enclosure cap with the size of 17.5cm long, 12.9cm width and 2.1cm height is designed. A projecting flat rim with 0.3cm deep and 0.5 cm width is designed at the end on the cap which provides a space for rubber O-ring to bind at the cap in order to seal the enclosure box fully. Figure 3.8 shows the projecting flat rim at the end enclosure cap. Figure 3.9 shows the O-ring with 0.4cm diameter and 46cm length.

After designing all the parts, pre-assembly is done using Solidworks assembly to make sure all the parts fit each other before sending to fabrication at UTeM Mechatronic Lab. After the enclosure is done fabricate and the box will test waterproof for the time duration. There is two type of waterproof test will be done. First is the enclosure box test, and the second is the enclosure cap waterproof test. The experiment procedure is discussed in chapter 3.8.

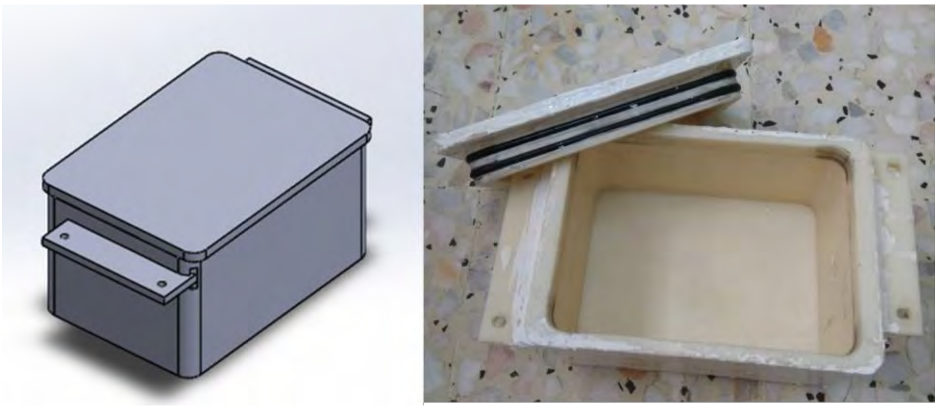


Figure 3.6: Battery Enclosure Box

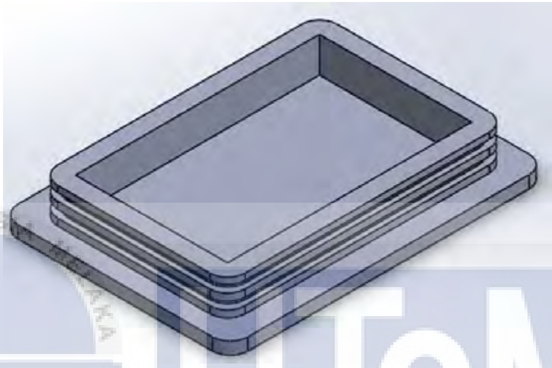


Figure 3.7: Enclosure Cap

Figure 3.8: Front View of Cap showing the projecting flat rim design

Figure 3.9: O-ring

3.5.4 Propulsion System

Generally, the propulsion system is a machine that produces a force to driving or pushing forward and backward. Thruster which consists of motor and propeller. First, there are two aspects to be considered when choosing a propeller for AUV, which is propeller pitch and diameter. Pitch is the distance of a propeller after a revolution, for example, a 19-pitch propeller will thruster the vehicle forward 19 inches in one revolution. Diameter is the length of the across the center point of the propulsion machine. Propeller blades are varying from 2 blade propeller up to 6 blade propeller and more. Table 3.1 propeller shows the difference between fix pitch propeller and controllable pitch. Usually, 2 blades and 3 blade propellers are usually used by the underwater vehicles especially AUV.

Table 3.1: Comparison of different type of propeller pitch [33]

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 the system does 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 controllable pitch propeller.	Multifaceted and luxurious system

After comparison, the thruster suitable to use is BlueRobotics Thrusters T100 as shown in Figure 2.8 and Figure 3.10 made with two blades and a lower pitch. T100 Thruster is a low-cost, high-performance thruster for marine robotics. Table 3.2 shows the T100 specifications. It has a cable containing three wires connected to the three wires at the stator of the motor with 3 different phase and then connect to the electronic speed controller (ESC). 4 horizontal thrusters place beside the hull which 2 front and 2 at the back to gives a surge, sway and yaw motion, whereas another two vertical thrusters place inside the frame to gives the heave in both submersible and float actions. The thruster structure designs to place in symmetry to maintain AUV stability.

The design of AUV’s horizontal thruster configuration is vectored with the angle of 45 degrees, therefore some modification on the BlueROV is made. L-shaped support brackets are designed using Solidworks which shows in the Figure 3.11. The L-shaped bracket is 6cm long, 4cm width and 2.1cm height is to fix T100 thrusters to the AUV body. After the design is complete, Solidworks simulation is using the L-shaped bracket is stress tested. This test is to make sure the strength of the bracket is enough for holding the T100 thruster during the underwater operation.

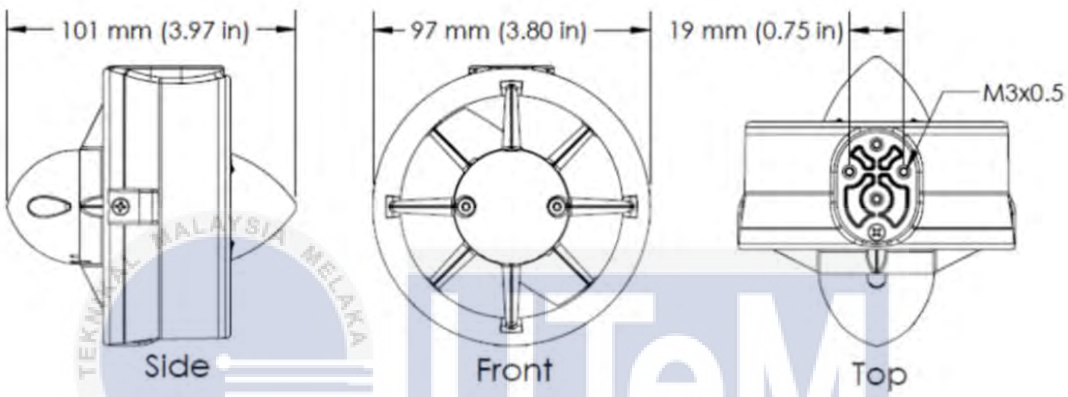


Figure 3.10: Dimension of T100 thruster [26]

Table 3.2 Specification of T100 Thruster

Parameter	**Value**
Model	BlueRobotics T100 Thruster
Maximum forward/backward thrust	23N / 18 N
Rotational Speed	300-4200 rev/min
Operating voltage/ Max current/ Max power	6-16 volts/ 12.5 amps/ 135 watts
Length/ diameter/ weight (air)	102mm/ 100mm/ 295g
Propeller diameter	76mm

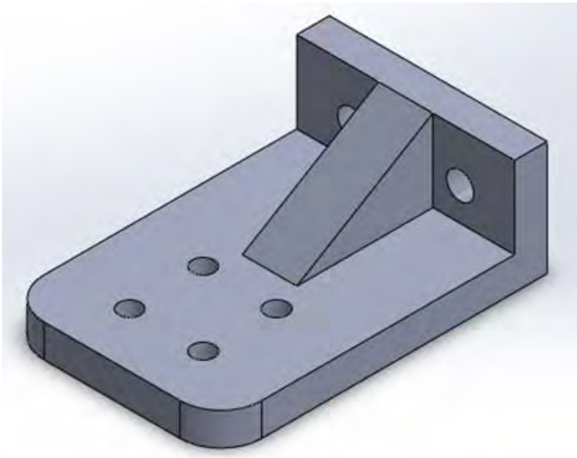


Figure 3.11: L-shaped support brackets

3.6 Electrical Description

Figure 3.12 and 3.13 shows the AUV is equipped with power supply circuit included Arduino UNO, Depth sensor MPX5700AP, 10 DOF IMU sensor, AfroESC 30A, 9V Energizer battery and 12V Lead-acid battery. The power supply provides 12V direct from battery to ESC for thrusters 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 or can be called as a depth sensor.

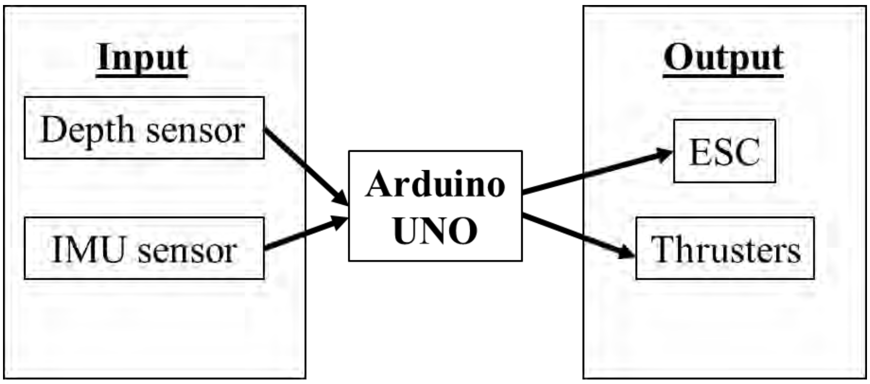


Figure 3.12: Block Diagram of the Embedded System Design

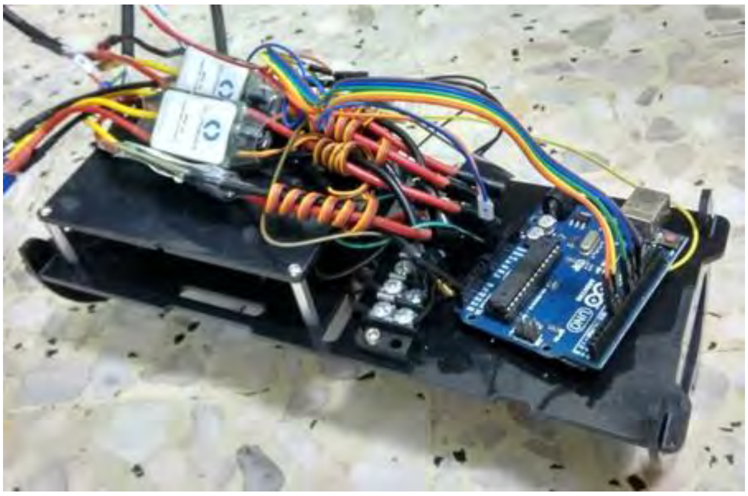


Figure 3.13: Electrical component with Electronics Tray

3.6.1 Electrical Power Supply

Based on the previous AUV project, lithium ion or lithium polymer is the best solution for power supply. However, due to budget issues, a lead-acid battery will be used instead of a lithium-ion battery. Figure 3.14 shows the 12V 7.2Ah lead-acid battery used to supply the ESC and thrusters since it required 6V-16.8V to work. Besides that, 9V energizer battery used to power up the Arduino since Arduino required only 7V-12V to work and it placed on the BlueROV electronic tray.

Figure 3.14: GP 12VDC battery and Energizer 9VDC battery

3.6.2 Depth Sensor

The pressure sensor is linked out through the pressure hull end cap. The pressure position detecting height of AUV movement and. 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 3.15. It has a pressure range from 15KPa to 700KPa; supply voltage range from 4.75VDC to 5.25VDC; the sensitivity of 6.4mV/KPa; maximum depth up to 70 meters. Pin configuration of this pressure sensor is shown in Table 3.3.

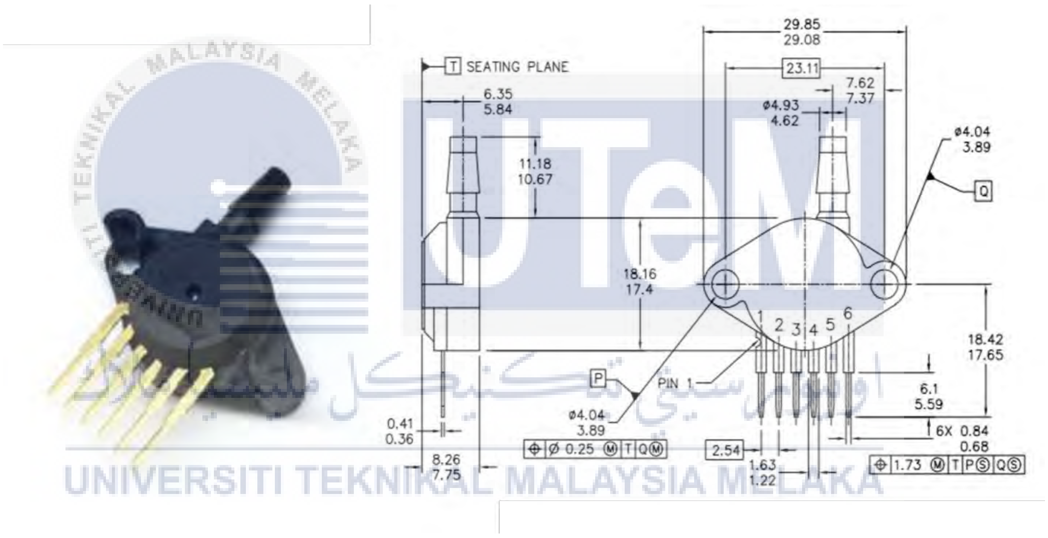


Figure 3.15: MPX5700AP pressure sensor

Table 3.3 MPX5700AP Pinout configuration

Pin Number	Function
1	V(out)
2	Ground
3	V(cc)
4	V1
5	V2
6	VEX

3.6.3 10 DOF IMU Sensor

Figure 3.16 shows the 10 DOF IMU which is a GY-80 sensor. This IMU sensor is good at motion monitoring, detecting and measuring the position, height and temperature because this GY-80 consist of the magnetometer, gyroscope, barometer, thermometer, and accelerometer. It would be helpful for balancing robot by measure the heading degree of the AUV. Table 3.4 shows it the data of each sensor. Currently, for this AUV project, the scope is only focused on a magnetometer which is to maintain the stability of in yaw rotation control. The other axis of gyro and accelerometer will do in future work because it needs more thrusters to support the motion.

The first step to use MC5883L magnetometer is to initialize the magnetometer by defining the register addresses given in the date sheet and some variables. After that, the magnetometer needs to make sure in the normal mode during the setup and identify the sensitivity of the sensor. For the programming part, loop section is to read the data from the 3-axis of the magnetometer and then the raw data will be converted into the gauss unit by using mathematic calculation. The table 3.4 shows the resolution of the magneto sensor is 16 bits which are corresponding to the sensitivity of 0.92 mG/digit unit, therefore, the raw data need to multiply with 0.00092 in order to get the gauss unit in every axis of the magnetometer.

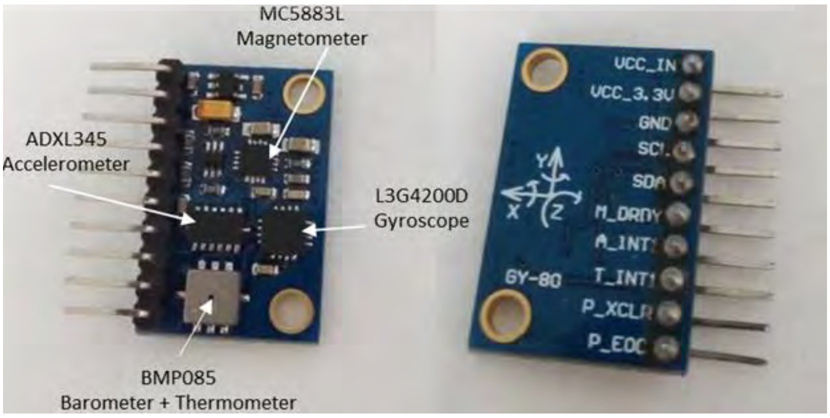


Figure 3.16: GY-80 IMU Sensor

Table 3.4: Date sheet for GY-80 sensor

Parameter	**Value**
Power supply	3.3 V-5.5 V (internal voltage regulation)
MC5883L (3-axis compass) Resolution: Sensitivity: Measurement range: Operating current:	 16 bit 0.92 mG/digit ±4800μT 280μA
L3G4200D (3-axis gyroscope) Resolution: Sensitivity: Measurement range: Operating current:	 16 bit 2000dps ±250, ±500, ±1000, ±2000°/sec 3.2 mA
BMP180 barometric pressure Resolution : Measurement range (configurable) : Accuracy :	 16~19 bit 300~1100hPa (altitude : +9000m~-500m) 0.02hPa(0.17m)
ADXL345 (axis accelerometer) Resolution : Measurement range (configurable) : Operating current :	 16 bit ±2, ±4, ±8, ±16g 450μA

3.6.4 Arduino UNO-R3

The AUV equipped with Arduino UNO R3 as the main board to control the AUV shown in Figure 3.17. The microcontroller operates inside Arduino is an ATmega328. 14 digital output pins which consist of 6 PWM outputs, besides that, 6 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. Arduino UNO can accept input voltage from 7V to 12 V, thus the 9 VDC is selected to turn on the board.

The output port for PWM is important for AUV speed controller, which is ESC that use PWM signal to give instructions to thrusters. In this AUV project, all 6 PWM output port is used for 6 thrusters which including 4 horizontal thrusters and 2 vertical thrusters.

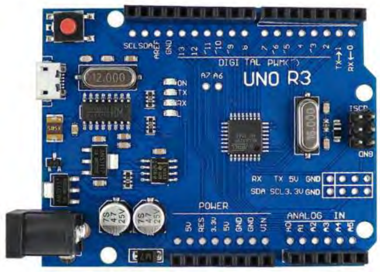


Figure 3.17: Arduino UNO R3 board

3.6.5 Afro ESC 30A

Figure 3.18 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 of it able to integrate with the brushless motor mentioned before and it also can provide a 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.

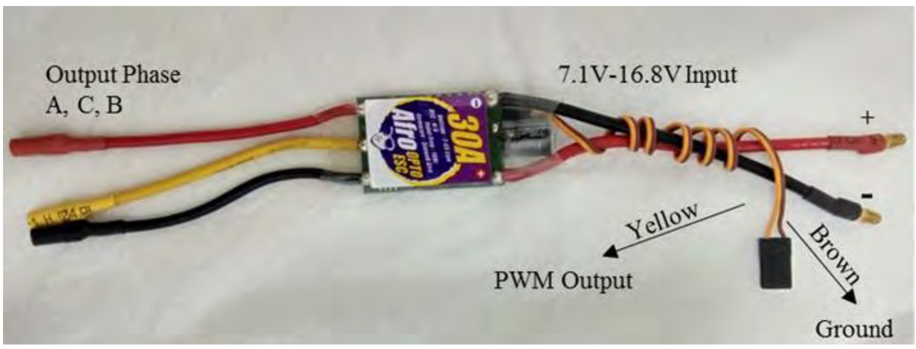


Figure 3.18: Afro 30A Electronic Speed Controller

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 assembled part is open to 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 assembled part is open 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 cursor 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 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 3.19.

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 the pool).
c) Measuring Tape with 3m long.
d) Weighing Device with 50Kg maximum weight.
e) Multi-meter for all electronic circuit test.

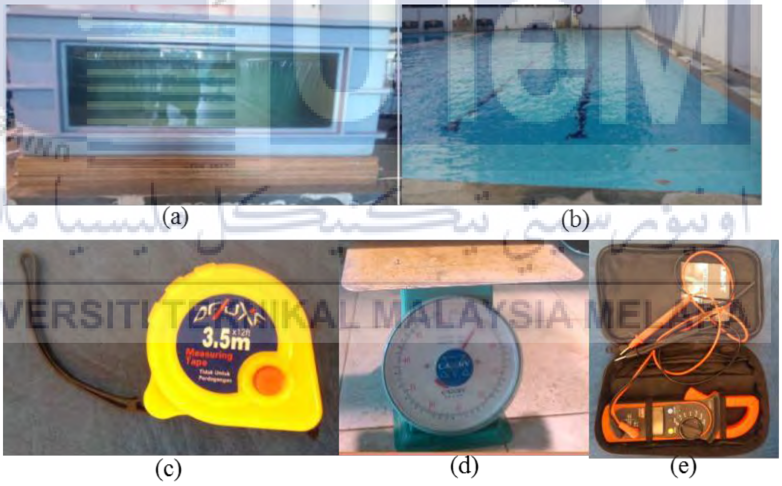


Figure 3.19: Equipment used in experimental tests

3.8.1 Experiment 1: Enclosure Box Material Waterproof Test

Objective: To study and test the waterproof for the material used (PLA) for battery enclosure box for AUV.

Parameters: Manipulated Variable: Time

Responding Variable: Present of water leakage

Apparatus: Battery enclosure box, enclosure cap, 2kg load, rule

Procedure:

1. Enclosure box without a cap is placed in the bucket.
2. 2 kg load is loaded into the box to avoid the box floating up.
3. Water is filled into the bucket which the water level must almost reach the height of the enclosure box but not over the height of the box.
4. Prevent the water flow into the box during the loading process.
5. After 5 min the level of water level inside the box is observed and recorded.
6. Step 5 is repeated with time 10 min, 15 min, 20 min and 25 min.
7. The results then recorded and tabulated in table form.
8. Make sure the bottom of the enclosure box is totally dry.
9. The enclosure end cap is close up with the enclosure box.
10. The box is fully immersed in a water for 5 min shown in Figure 3.21.
11. Open up the cap of the box and recording the result of water leakage.
12. Step 8 until step 11 is repeated with other time duration which is 10 min, 15 min, 20 min and 25 min.
13. The results then recorded and tabulated in table form.

Figure 3.20: Enclosure box waterproof test

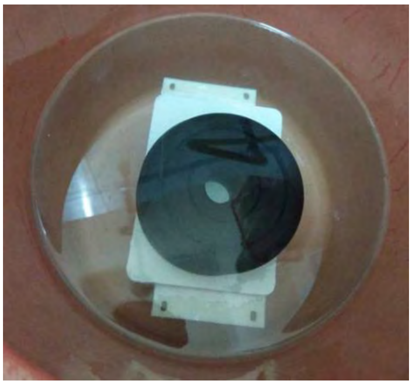


Figure 3.21: End cap waterproof test

3.8.2 Experiment 2: AUV Waterproof Test

Objective: To study and test the waterproof for the pressure hull and electronic enclosure box for AUV.

Parameters: Manipulated Variable: Time and Depth

Responding Variable: Level of water leakage

Apparatus: AUV, pressure hull, battery enclosure box, measuring tape.

Procedure:

1. The water is filled in the pool to approximately 0.50 meter height.
2. Enclosure box and pressure hull is closed tightly with the end cap.
3. The AUV is then submerged until around 0.5 meters from the water surface.
4. It takes out from the pool after 5 minutes and checks whether the water leaking.
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 with changing to depth control by submerge it 0.2m from water surface for 10 minutes and follow by 0.4m, 0.6m, 0.8m and 1.0m.
7. The result is then recorded and tabulated in table form.

Figure 3.22: Waterproof test for AUV

3.8.3 Experiment 3: Balancing Test

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

Parameters: Manipulated Variable: Size of polystyrene
Responding Variable: Movement of AUV

Apparatus: AUV, load, polystyrene.

Procedure:

1. The AUV is put into a lab pool without any weight attached and then balance it under the water.
2. The load and polystyrene is added to the AUV depending on the balancing.
3. The load is added to submerged down the AUV while polystyrene is to increase the buoyancy of AUV.
4. The AUV is then submerged until it reached stability.
5. AUV is run with the weight attached to it.
6. The forward movement of the AUV is observed whether it moves in a straight line.
7. Step 2 to 6 is repeated 10 times.
8. The observation is then recorded and tabulated in table form.

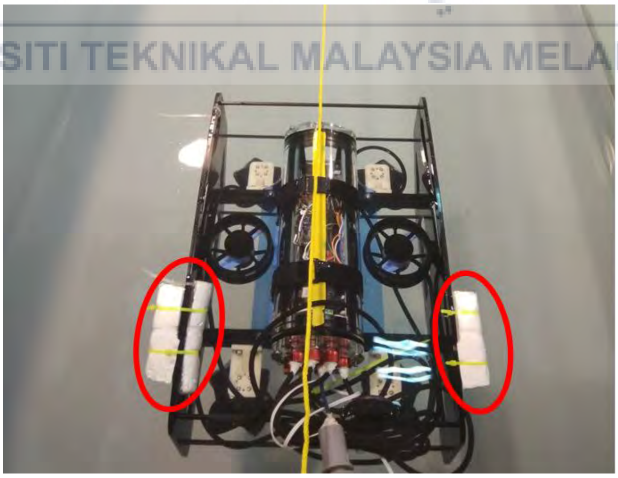


Figure 3.23: Polystyrene attached beside AUV.

3.8.4 Experiment 4: 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 gadget.

Procedure:

1. The AUV is measured weight by hanging it from the string of weighting device with no weight appended as shown in figure 3.24(a).
2. AUV is lower down into the water until the weighting device shown zero reading, while it isn't touching the sides or base of the pool.
3. Remain the length of the hanging string and a 250g load is attach to the AUV.
4. Step 2 and 3 is repeated by appended the weight to AUV with an alternate mass as shown in figure 3.24(b).
5. The perception is then recorded and organized in table form.
6. Calculate the buoyant force by taking the contrast between the mass in the air and the mass in water.

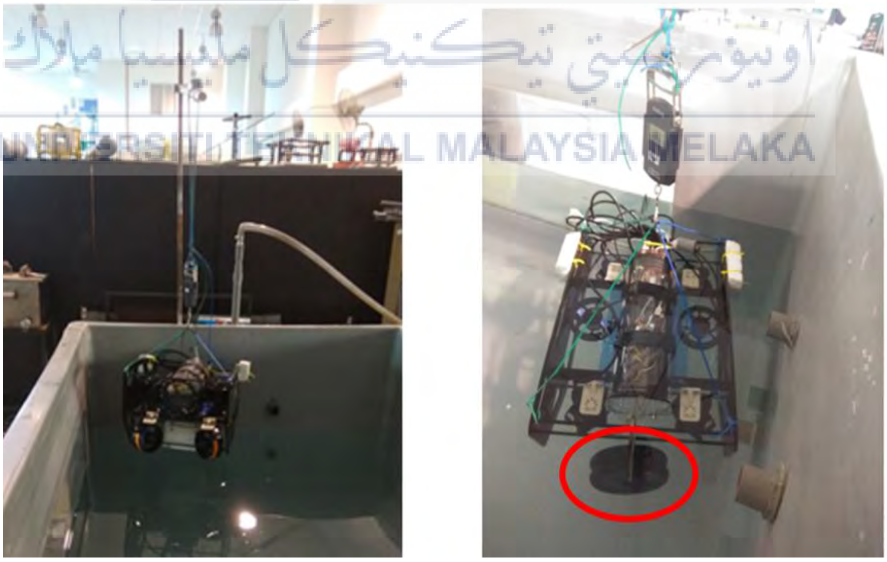


Figure 3.24 (a)   Figure 2.24(b)

Figure 3.24: AUV hanging by the weighting device

3.8.5 Experiment 5: Pressure (Depth) Test

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

Parameters: Manipulated Variable: Depth

Responding Variable: Voltage/pressure

Apparatus: Depth sensor, AUV, measuring tape, USB cable.

Procedure:

1. The swimming pool used up to approximately 1.2 meter height as shown in figure 3.25(a).
2. The pressure sensor is inserted into pressure hull and connected to Arduino by using the long wire for serial monitor to the computer.
3. The AUV is then submerged into pool and pressure sensor will start detecting the pressure value as shown figure 3.25(b).
4. The output signal voltage of depth sensor is obtain from the serial monitor.
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 the theoretical and actual pressure measured by the sensor is plotted and also the output voltage obtained from the sensor.

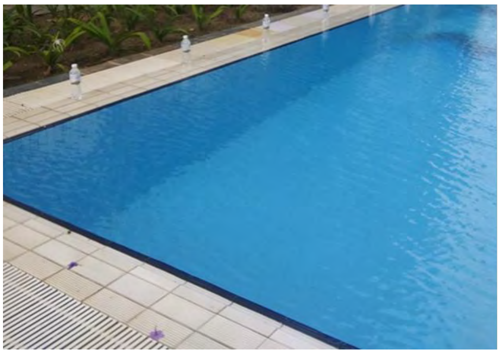


Figure 3.25(a)

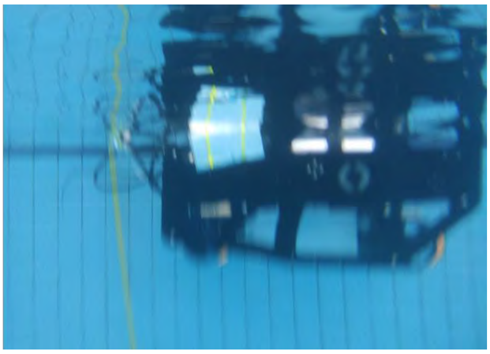


Figure 3.25(b)

Figure 3.25: AUV depth test

3.8.6 Experiment 6: Yaw Correction Test

Objective: To determine the standard deviation of the yaw correction of AUV.

Parameters: Manipulated Variable: Angle of rotation

Responding Variable: Deviation angle

Apparatus: GY-80 IMU sensor, USB cable, protractor ruler, lab pool.

Procedure:

1. The GY-80 sensor is connected to the Arduino and the sensor is in the normal direction inside the pressure hull.
2. One straight line string is assigned in the pool as the reference angle for the AUV as shown in figure 3.26(a).
3. Different yaw angle base on the straight string is also assigned using the string as shown in figure 3.26(b).
4. AUV is placed in the straight line under the water base on the straight string.
5. Switch on the AUV and record the initial reading of AUV in term of magnetometer field in y-direction by serial monitor.
6. Manually rotate the AUV in yaw direction to the ±15º and let the AUV to rotate back to its original position and the final magnetometer field is recorded.
7. Step 6 is repeated 5 times to get more accurate result.
8. Step 4 to 7 is repeated with ±30º, ±45º of yaw rotation.
9. Compare the field before and after the yaw rotation to calculate the standard deviation of the yaw correction.

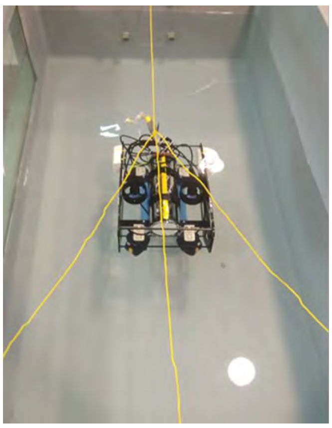


Figure 3.26(a)

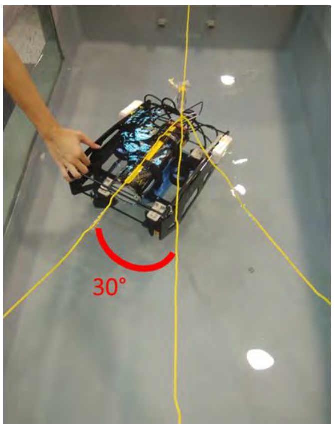


Figure 3.26(b)

Figure 3.26: AUV yaw rotation test.

3.8.7 Experiment 7: Speed test

Objective: To measure and determine the speed of AUV

Parameters: Manipulated Variable: PWM, distance

Responding Variable: Time

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 as shown in figure 3.27(a).
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(b).
4. Step 3 is repeated by changing the forward PWM to 1700; backward PWM 1300 and 1400.
5. The observation is then recorded and tabulated in table form.
6. A graph of distance versus time is plotted and analysed.

Figure 3.27(a)

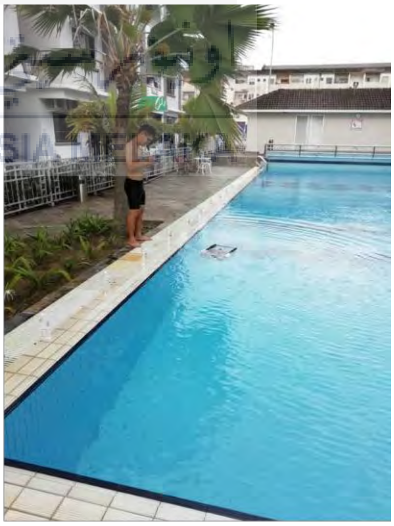


Figure 3.27(b)

Figure 3.27: AUV speed test at swimming pool

3.8.8 Experiment 8: Turning test

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

Parameters: Manipulated Variable: PWM

Responding Variable: Time

Apparatus: AUV, stopwatch, swimming pool

Procedure:

1. All the equipment includes weight and sensors were attached in the AUV.
2. AUV is turn left when left thrusters moves with 1400 backward PWM but right thrusters move with 1600 forward PWM and the time taken for AUV to turn 90º is recorded as shown in Figure 3.27.
3. Step 3 is repeated by changing the PWM to 1350; 1650, 1300; 1700, 1250; 1750 and 1200; 1800.
4. Step 3 to 4 is repeated by changing the turning direction from left to right.
5. The observation is then recorded and tabulated in table form.

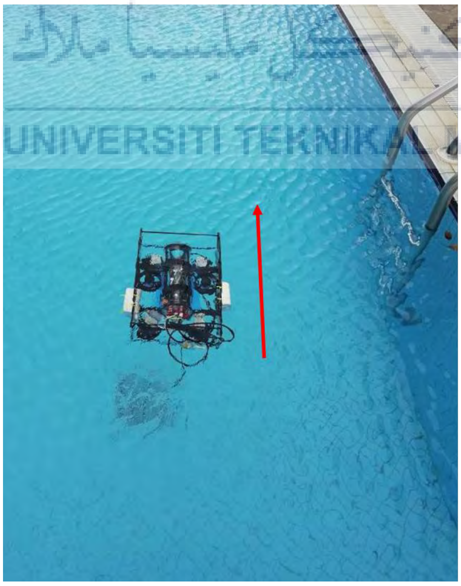


Figure 3.28(a)

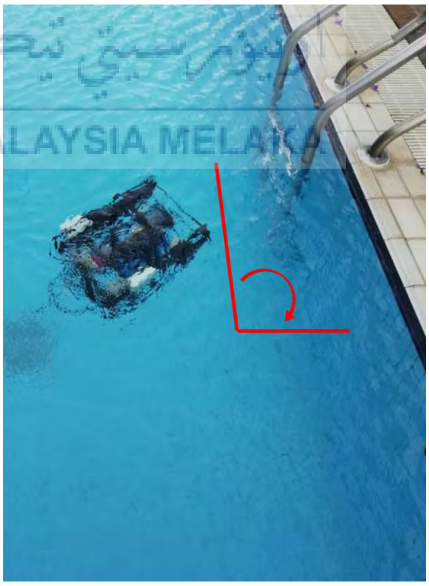


Figure 3.28(b)

Figure 3.28: Turning test in swimming pool

3.8.8 Experiment 9: Straight line moving test

Objective: To make sure the AUV is moving in straight line.

Parameters: Manipulated Variable: Distance between gate and starting zone

Responding Variable: Straight line movement

Apparatus: AUV, measuring tape, PVC gate.

Procedure:

1. A straight path is setup under the water by using PVC gate and a starting zone as shown in figure 3.29(a).
2. The distance between the gate and starting zone is set to 5 meter.
3. AUV is switch on at the starting zone and let the AUV to pass through the gate as shown in figure 3.29(b) and the result of AUV movement is observed and recorded.
4. Step 2 to 3 is repeated 10 times
5. Step 2 to 4 is repeated with the distance of the gate change to 6m, 7m, 8m, 9m and 10m respectively.

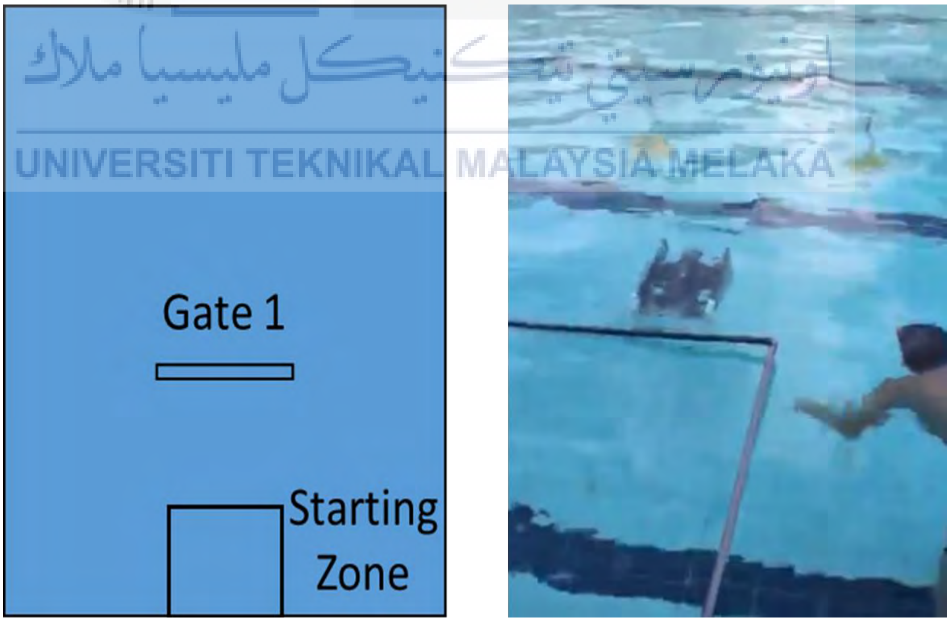


Figure 3.29(a) Figure 3.29(b)

Figure 3.29: PVC gate and starting zone setup

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 last part of Chapter 3.

CHAPTER 4

RESULT & DISCUSSION

4.1 Introduction

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

For the current state, the AUV only can reach the preliminary result and some analysis using SolidWorks. The first experiment tested for the AUV part is waterproof for AUV electronic enclosure box and cap. Next, the results obtained from the analysis in SolidWorks are analysed and discussed. The analysis done in SolidWorks included the center of mass, stress and displacement test. Next, the experiment will proceed in next semester is the experiments on the AUV hardware part which are included balancing of the AUV and buoyancy of the AUV. Next, the depth, IMU, speed and turning test preparation 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 the 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 a good knowledge of its center of gravity location.

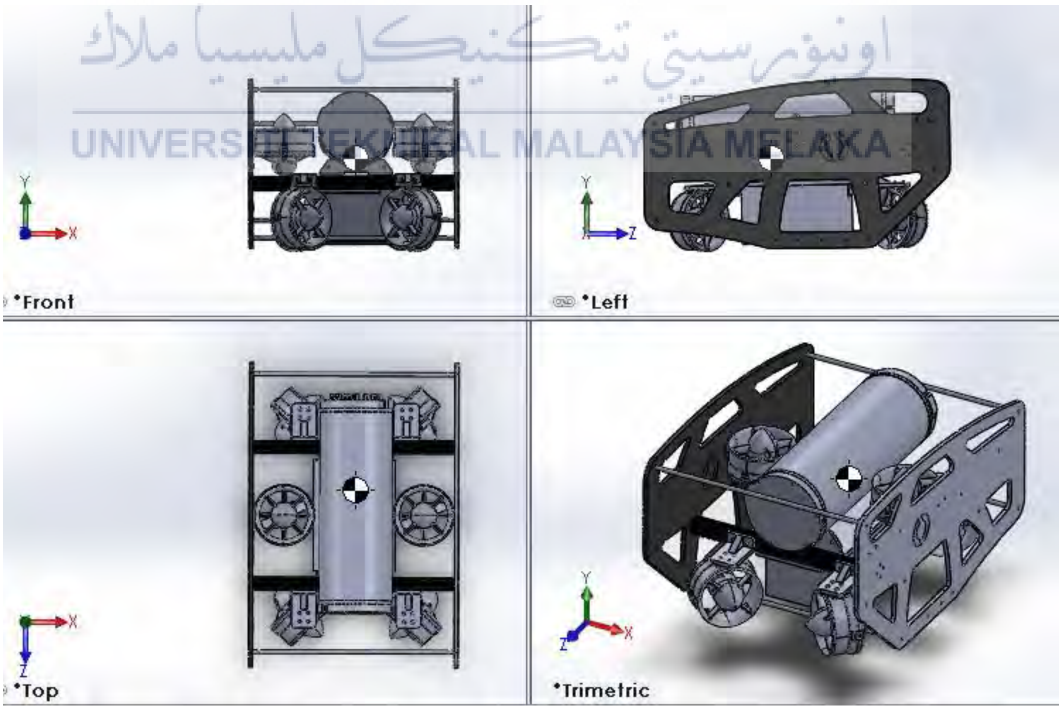


Figure 4.1: Different view of AUV center of mass

Table 4.1: Center of mass in SolidWorks Mass Properties

Axis	Center of mass (cm)
X	42.28
Y	55.48
Z	42.56

Based on the mass properties Table 4.1, it's clearly shown that the center of mass for AUV is placed at 42.28cm X-axis, 55.48cm Y-axis, and 42.56cm Z-axis. The COM also simulate for AUV mechanical parts include a frame, hull, enclosure box, and thruster.

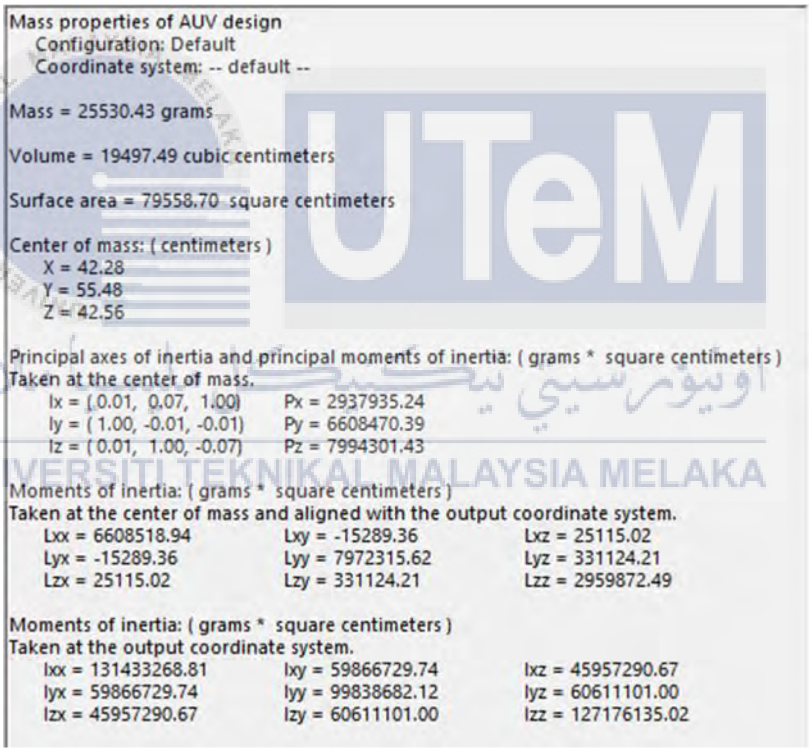


Figure 4.2: Result of mass properties form SolidWorks

4.1.2 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 Poly Lactic Acid (PLA) as the main material for the enclosure box and other fabricated parts. 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 analysis of the enclosure box is first determined by applying 3 meter underwater pressure to the box as shown in Table 4.2 to Table 4.11. The different pressure exerted to the box will be simulated by using 1 meter depth until 10 meter depth and the result will show in below.

Table 4.2: Model Information (enclosure box)

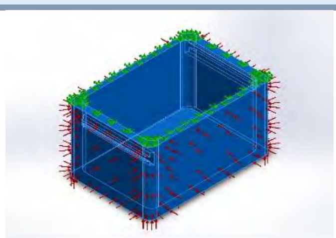
Solid Bodies			
Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
	Solid Body	Mass:0.522409 kg Volume:0.000512166 m^3 Density:c Weight:5.11961 N	C:\Users\zhe99\Desktop\FYP\drawing\Enclosure Box.SLDPRT Nov 28 00:30:18 2017

Table 4.3: Material properties

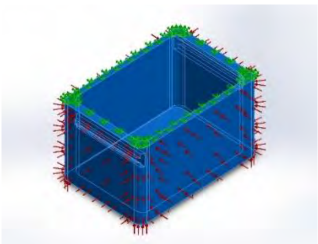
Model Reference	Properties	Components
	Name: **'PLA** Model type: **Linear Elastic Isotropic** Default failure criterion: **Max von Mises Stress** Yield strength: **5.9984e+007 N/m^2** Tensile strength: **5.309e+007 N/m^2**	**SolidBody 1(Fillet5)(Enclosure Box)**

Table 4.4: Fixture definition

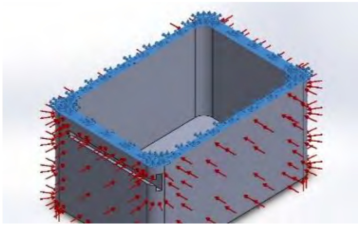
Fixture name	Fixture Image	Fixture Details
Fixed-1		**Entities:** **1 face(s)** **Type:** **Fixed Geometry**

Table 4.5: Load definition

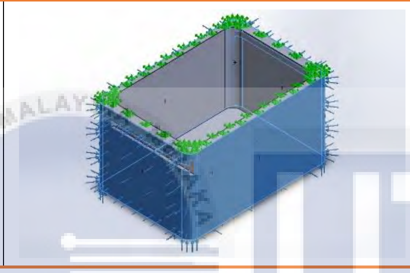
Load name	Load Image	Load Details
Pressure-1		**Entities:** **9 face(s)** **Type:** **Normal to selected face** **Value:** **29430** **Units:** **N/m^2**

Table 4.6: Mesh properties

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	0.800289 cm
Tolerance	0.0400144 cm
Mesh Quality Plot	High

Table 4.7: Mesh Information Details

Total Nodes	15696
Total Elements	8161
Maximum Aspect Ratio	5.0076
% of elements with Aspect Ratio < 3	95.5
% of elements with Aspect Ratio > 10	0
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	00:00:01
Computer name:	ZHE

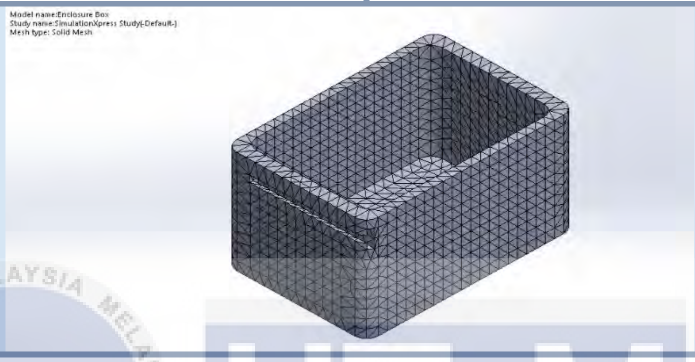
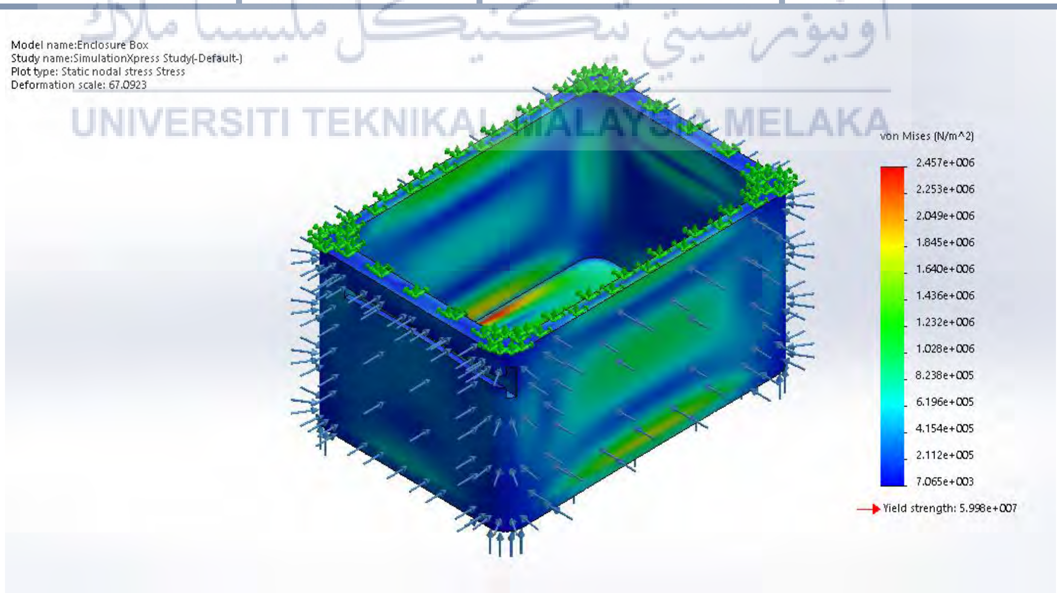


Table 4.8: Study Results for Stress

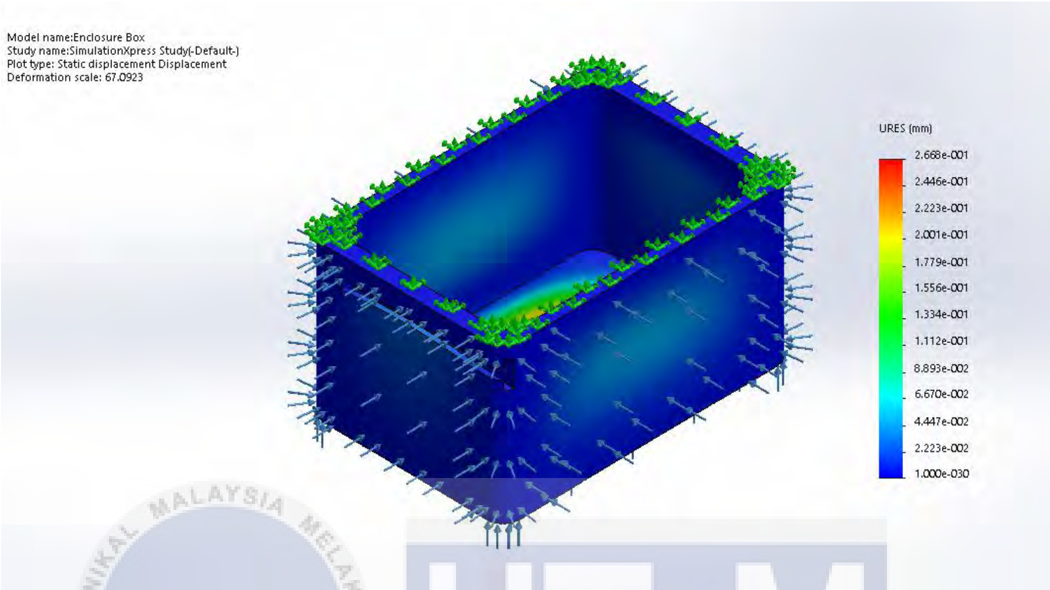
Name	Type	Min	Max
Stress	VON: von Mises Stress	7.065e+003N/m^2 Node: 3394	2.457e+006N/m^2 Node: 7080



Enclosure Box-SimulationXpress Study-Stress-Stress

Table 4.9: Study Results for Displacement

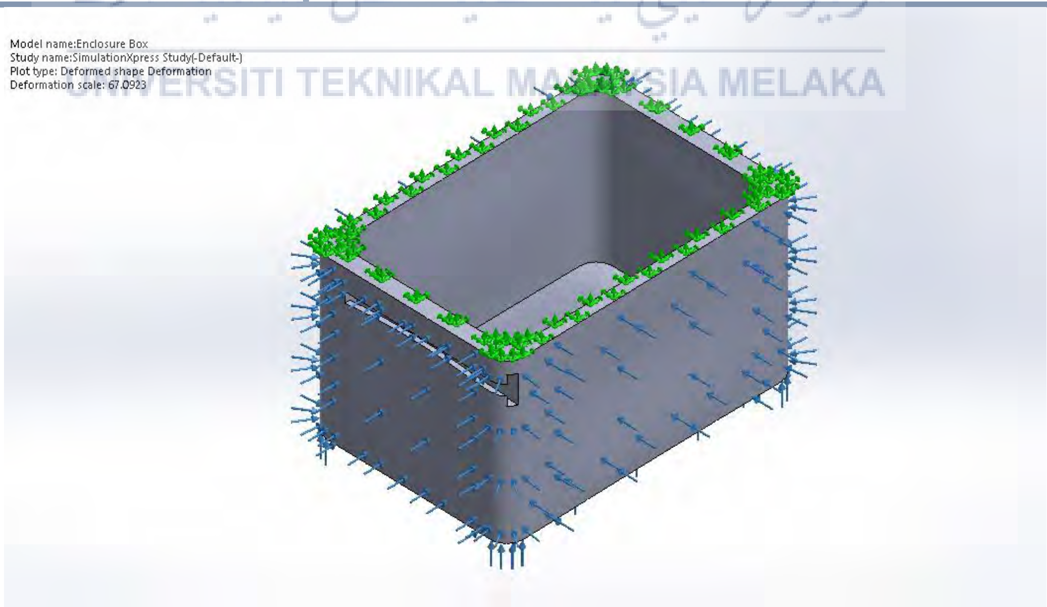
Name	Type	Min	Max
Displacement	URES: Resultant Displacement	0.000e+000mm Node: 1	2.668e-001mm Node: 9059



Enclosure Box-SimulationXpress Study-Displacement-Displacement

Table 4.10: Study Results for Deformation

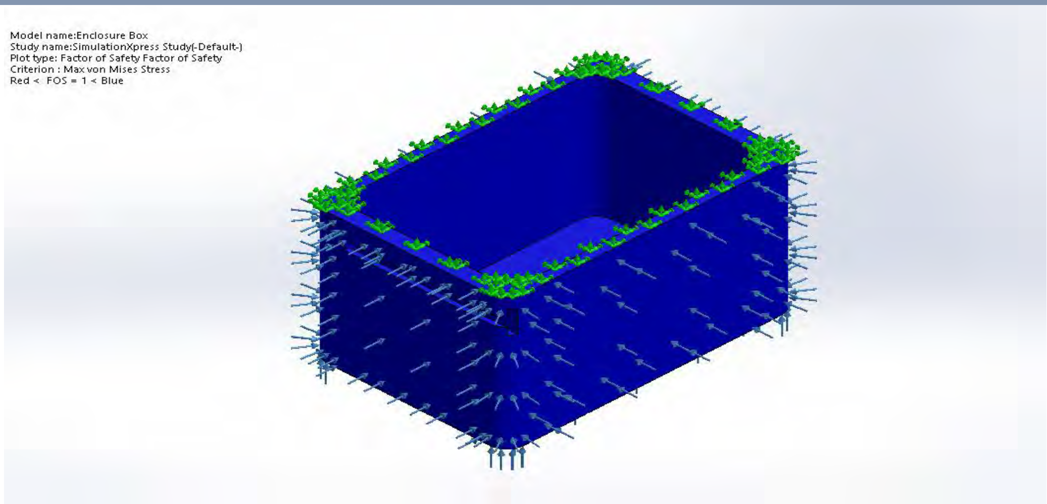
Name	Type
Deformation	Deformed shape



Enclosure Box-SimulationXpress Study-Displacement-Deformation

Table 4.11: Study Results for Factor of safety

Name	Type	Min	Max
Factor of Safety	Max von Mises Stress	2.441e+001 Node: 7080	8.491e+003 Node: 3394



Enclosure Box-SimulationXpress Study-Factor of Safety-Factor of Safety

Table 4.2 and 4.3 show the enclosure box has a 1020 Kg/m3 in density (0.522409 Kg, 0.000512166 m^3) with 59.984 MN/m^2 in yield strength and 53.09 MN/m^2 in tensile strength. As the maximum depth of this project is 3 meter as shown in the scope of this project, thus the fixture and load with 29.43 kN/m^2 pressure are exerted. The fixture of the finite element analysis of 3 meter underwater pressure is shown in Table 4.4 and Table 4.5. The mesh property is shown in Table 4.6 and 4.7. Some of the study tests are simulated include the stress simulation (Table 4.8), displacement simulation (Table 4.9), deformation simulation (Table 4.10) and safety factor simulation (Table 4.11).

From the result in Table 4.8, the maximum stress 2.457 MN/m^2 is on the enclosure box since only 29.43 kN/m^2 is applied. By referring to the safety factor the material is fully safe since in blue color. Since PLA has 59.984 MN/m^2 yield strength. The relation between the depth and maximum stress on the box is taken by simulating from 1 meter depth to 10 meter depth as shown in Figure 4.3.

Water pressure $P = \rho g h$ (4.1)

$\rho = 1000$ kg/m^3

$g = 9.81$ m/s^2

Table 4.12: Relation between depth and water pressure and Max stress

Depth (m)	Water pressure (kN/m2)	Max stress (kN/m2)
1	9.81	819.1
2	19.62	1638
3	29.43	2457
4	39.24	3276
5	49.05	4095
6	58.86	4914
7	68.67	5733
8	78.48	6553
9	88.29	7372
10	98.10	8191
73.2 (Permanent deformation start)	718.10	59960

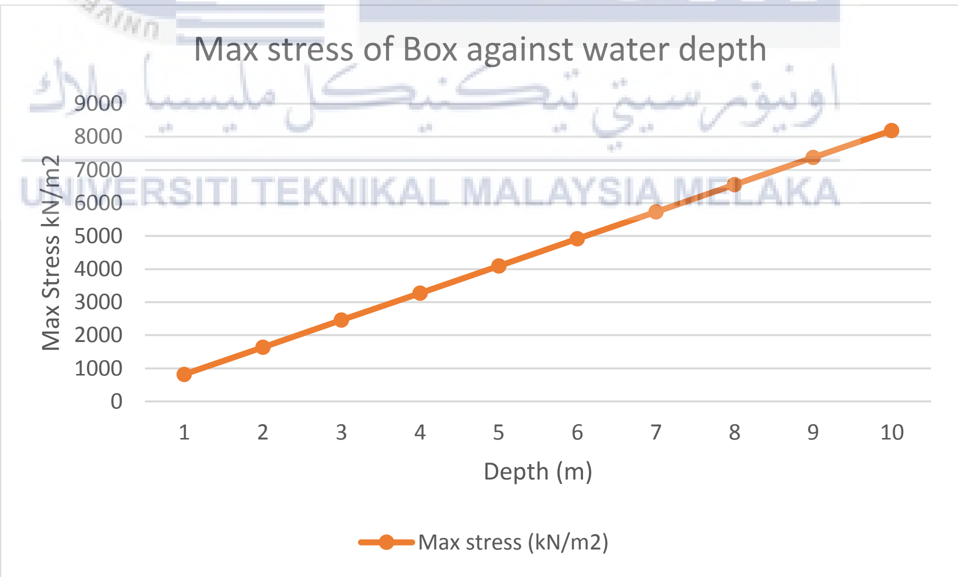


Figure 4.3: Graph of Maximum stress versus water depth

Since the yield strength of the material used can withstand up to 59.984 MN/m^2

Let M is the gradient of the graph

$$M = \frac{7372k - 5733k}{9 - 7} = 819500$$

$$\frac{59984k - 7372k}{h - 9} = 819500$$

h = 73.2m

The maximum depth for the enclosure box can go underwater is about 73.2 meter to ensure the box is without permanent deformation. The permanent deformation will start after the box go beyond this maximum depth. Table 4.12 above shows the result from the Solidworks Simulation.

4.2 Experiment Results

4.2.1 Experiment 1: Enclosure Box Material Waterproof Test

Results obtained from the experiment is recorded and analysed as shown in table form. Table 4.13 shows the result of waterproof test about the material used which is PLA as shown in the Figure 3.20. Table 4.14 shows that the result of the waterproof test between enclosure cap and enclosure box as shown in Figure 3.21.

Table 4.13: Waterproof test for Enclosure Box material

Time (min)	Bottom of the box	Waterproof
5	Dry	yes
10	Dry	yes
15	Dry	yes
20	Dry	yes
25	Dry	yes

Table 4.14: Waterproof test for Enclosure Cap

Time (min)	Bottom of the box	Waterproof
5	Dry	yes
10	Dry	yes
15	Dry	yes
20	Dry	yes
25	Little Wet	no

From the waterproof for enclosure box material experiment is to ensure the material (PLA) used for fabricating this enclosure box is waterproof. The result from Table 4.13 concludes that the PLA material is suitable for underwater used. After 25 minutes immersion into the water and no leakage occur into the enclosure box.

The result of waterproof between enclosure cap and enclosure box is showing a good waterproof within 20 min and after 25 min a little water is leak in the enclosure box. This result showing that some sealant must be applied to the gap between the cap and box to ensure a good waterproof result.

4.2.2 Experiment 2: AUV Waterproof Test

Results obtained from the experiment is recorded and analysed as shown in Table 4.15 and 4.16. The height (0.5m) of the lab pool is being measured to calculate the water pressure exerted. The equation is based on fluid pressure principle which is

$$P_{static\ fluid} = \rho g h \quad (4.2)$$

Where (ρ = fluid density; g = acceleration of gravity; h = depth of fluid)

$$P_{static\ fluid} = 1000\ kg/m^3 \times 9.81\ N/kg \times 0.5m$$
$$= 4.905\ kN/m^2\ (kPa)$$

Table 4.15: Waterproof Test for time controller (0.5 meter depth)

Time (minutes)	Water in	Waterproof
5	No	Yes
10	No	Yes
15	No	Yes
20	No	Yes
25	No	Yes

Table 4.16: Waterproof Test for depth controller (10 minutes)

Depth (meter)	Water in	Waterproof
0.2	No	Yes
0.4	No	Yes
0.6	No	Yes
0.8	No	Yes
1.0	No	Yes

Based on Table 4.15 and Table 4.16, the AUV able to prevent the water flow in and shown the good result in waterproofing. This pressure hull and enclosure box are sealed with rubber O-ring which provides a tight surface between the hull and the caps. If the water leaking is happening with a small amount and this will be acceptable. This is because all the electronic components are put on the electronic tray which is about 3.5cm high from the bottom of the hull (Figure 4.4). Thus, these components are not to touch with water although a small amount of water leak in. The silicon sealant which seals the wire of the thrusters through the end cap of the hull. needs to check frequently to prevent water leaking from the gaps.

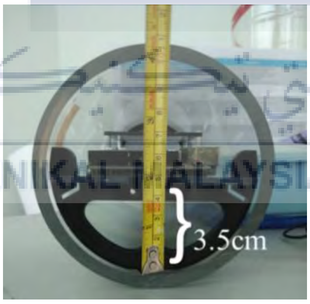


Figure 4.4: The plate inside PVC hull

4.2.3 Experiment 3: Balancing Test

The complete assemble AUV which including a battery and enclosure box cause the center of gravity of the whole AUV body move backward. Therefore addition of polystyrene needs to add on the back of AUV. The reason for balancing test is to balance AUV back and make sure it moves in forward with the straight line without any problems. Table 4.17 shows the observation for AUV balancing test with the forward motion.

Table 4.17: Observation of AUV forward movement

Volume of polystyrene (cm^3)		**Balance**	**Observation**	**Adjustment**
Left back	Right back			
50	50	No	Head of AUV pitch up and the tail is moving downward and bias to left very fast	Adjusting the polystyrene position and attach more polystyrene at tail especially on left back
150	100	No	Head of AUV pitch up partially and the tail is moving downward and bias to left fast	Adjusting the polystyrene position and attach more polystyrene at tail especially on left back
220	150	No	Head of AUV pitch up slowly and the tail is moving downward and bias to left slowly	Attach some polystyrene at tail especially on left back
300	198	Yes	AUV is moving in a straight line and the tail is bias to left very slowly	Attach some polystyrene at left back
314	198	Yes	AUV is moving in a straight line and the head and tail is balance	Coat a liquid rubber layer on the polystyrene to prevent the polystyrene worn

From the observation in Table 4.17, AUV with different dimension will have different results and create a balance motion. The polystyrene tie together with AUV by cable ties. The unbalanced weight of electronic component inside the enclosure box and pressure hull causing left back of the AUV become heavier and it also caused the center of gravity move to the left. Thus, AUV move curve instead of straight line. Therefore, adjusting the position of polystyrene should be made and the addition of polystyrene is needed. Based on the experiment, it showed that AUV balance only when the polystyrene is 314cm^3 at left back while 198cm^3 at right back 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.

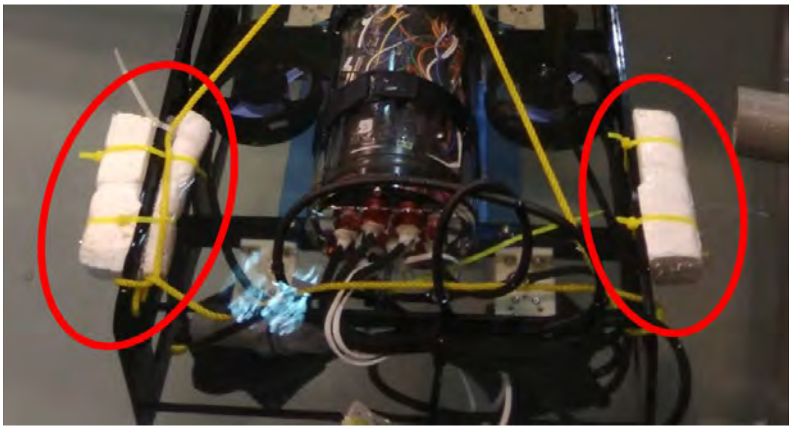


Figure 4.5: Different size of polystyrene is attached to left back and right back

4.2.4 Experiment 4: 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 the 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 4.18: Buoyant force acting on AUV

Mass of AUV without weight attached = 8.64 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
8.64	0.00	84.76	0.00	84.76
8.89	0.195	87.21	1.91	85.30
9.14	0.405	89.66	3.97	85.69
9.39	0.640	92.12	6.28	85.84
9.64	0.875	94.57	8.58	85.99
9.89	1.085	97.02	10.64	86.38
10.14	1.320	99.47	12.95	86.52
10.39	1.560	101.93	15.30	86.63
10.64	1.8	104.38	17.64	86.74

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

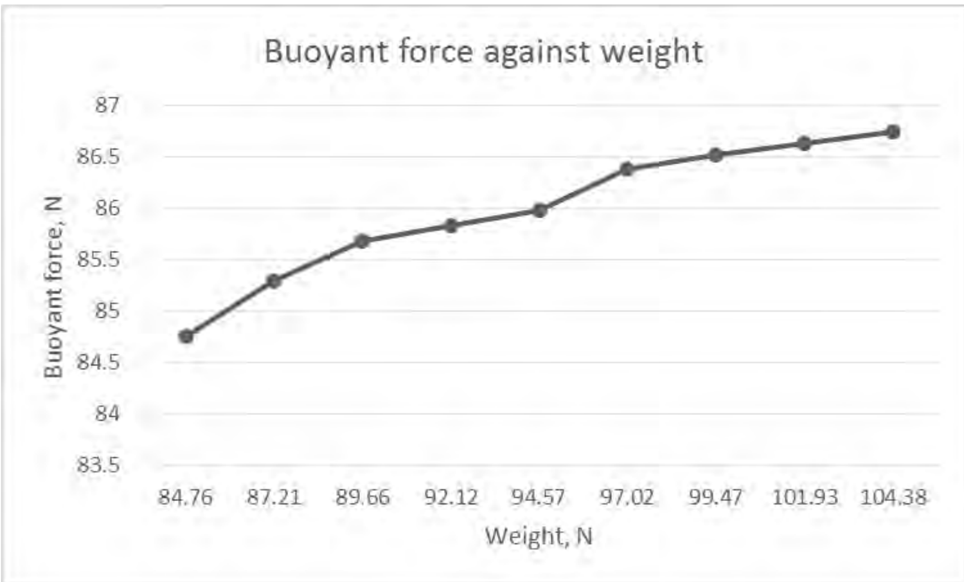


Figure 4.6: Graph of buoyant force against the weight

According to the Table 4.18, the mass of AUV initially is 8.64kg since this is the equilibrium mass as it neither float nor sink. The weight added to the AUV is 250g until the maximum weight attached is 2kg and the total is 10.64kg 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.

4.2.5 Experiment 5: 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 measurement method used is using the Arduino to measure the output signal voltage of depth sensor because the output signal voltage is very low. Table 4.19 shows the output signal voltage results with its depth.

Table 4.19: Output signal voltage

Depth (m)	Output Signal Voltage from serial monitor			
	First	Second	Third	Average
0	0.864	0.864	0.862	0.863
0.1	0.872	0.871	0.874	0.872
0.2	0.875	0.878	0.879	0.877
0.3	0.882	0.881	0.885	0.883
0.4	0.886	0.890	0.887	0.888
0.5	0.895	0.892	0.893	0.893
0.6	0.902	0.901	0.896	0.900
0.7	0.904	0.905	0.907	0.905
0.8	0.908	0.911	0.912	0.910
0.9	0.917	0.916	0.916	0.916
1.0	0.922	0.925	0.920	0.922

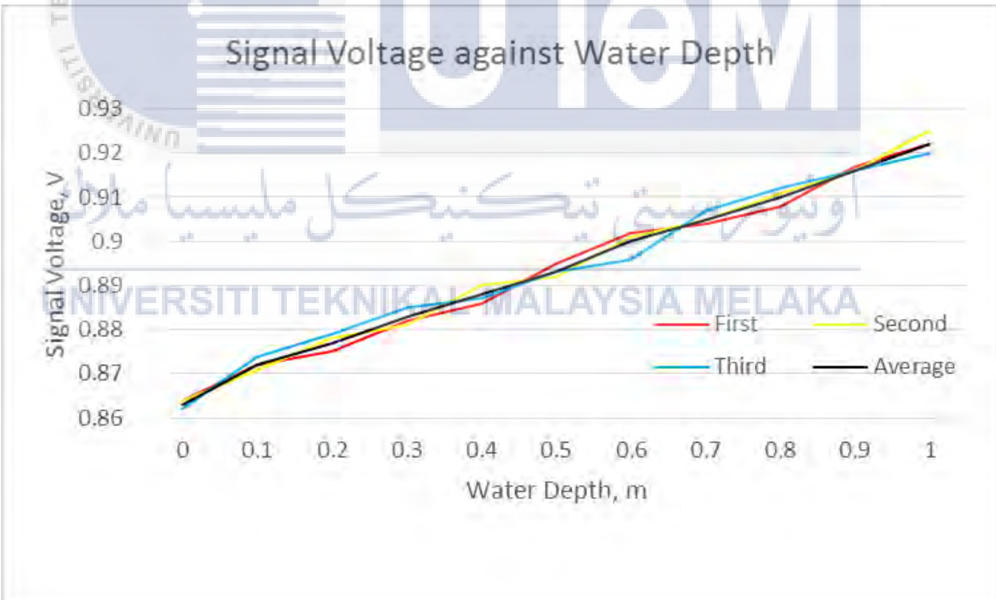


Figure 4.7: Graph of signal against water depth

$$\text{Actual Pressure, } P = \rho gh + 101.3\text{kPa} \qquad (4.3)$$

$$Vout = Vs * (0.0012858 * P + 0.04) \qquad (4.4)$$

$$\text{Measured Pressure, } P = \frac{\frac{Vout}{Vs} - 0.04}{0.0012858} \qquad (4.5)$$

$$\text{Percentage of error} = \frac{\text{Actual Pressure, } P(\text{kPa}) - \text{Measured pressure (kPa)}}{\text{Actual Pressure}} * 100\% \qquad (4.6)$$

Table 4.20: Actual and measured pressure

Depth, m	**Actual Pressure, P (kPa)**	**Measured Pressure, *P* (kPa)**	**Percentage of error (%)**
0	101.33	103.13	1.78
0.1	102.31	104.53	2.17
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	108.88	1.55
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

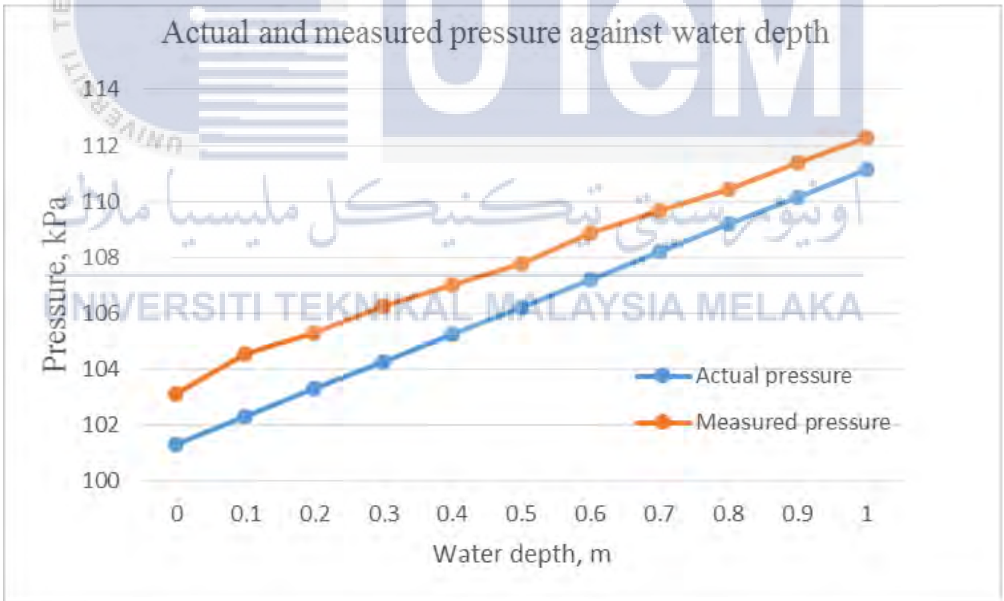


Figure 4.8: Graph of actual and measured pressure against water depth

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 but the depth test is did until 1 meter only since the swimming pool depth can only allow the AUV to reach that limit. The three readings of output are slightly different from each other but are almost the same. From Table

4.19 the setting depth between 0.863 V and 0.922 V is 1m. The theoretical pressure of this experiment can be obtained from the equation (4.3) by multiply the density of water (ρ) with depth (h) and gravitational acceleration (g). The measured pressure can calculate by using equation (4.5) where let Vs = 5V; Vout = average output voltage. Table 4.20 shows the value for actual and measured pressure and percentage of error.

From Table 4.20, 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 chlorine and some impurities will 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 4.9. 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 (4.7), p is pressure, w is weight of the fluid and h is the depth.

$$\Delta p = - w \Delta h \qquad (4.7)$$

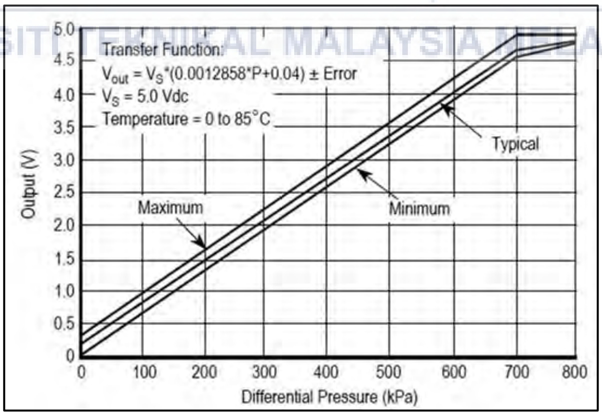


Figure 4.9: Output against absolute pressure (Datasheet)

As the result, MPX5700AP pressure sensor shows a good performance to measure the pressure value under the water. 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.

4.2.6 Experiment 6: Yaw Correction Test

The GY80-magnetometer sensor needs to be tested before used. The main purpose is to find out the deviation of the magneto sensor and the standard deviation. After the magneto sensor had calibrated, AUV will have the accurate value for yaw control. The output signal voltage is measured five times to get an accurate average output value. The measurement method used is using the Arduino serial monitor. Table 4.21 shows the output gauss in y-axis with its actual angle.

Table 4.21: Output gauss in y-axis with different angle of rotation

Degree of rotation, °	Y-axis output value after yaw correction (Gauss)					
	First	Second	Third	Fourth	Fifth	Average
-15	0.36	0.32	0.31	0.35	0.33	0.334
+15	0.33	0.34	0.36	0.35	0.33	0.342
-30	0.31	0.33	0.35	0.30	0.31	0.320
+30	0.37	0.35	0.33	0.35	0.33	0.346
-45	0.31	0.35	0.30	0.33	0.35	0.328
+45	0.33	0.36	0.36	0.35	0.32	0.344

$$\text{Deviation} = \text{Average} - \text{Actual} \quad (4.8)$$

$$\text{Standard deviation} = \frac{\text{deviations for all measurements added together}}{\text{number of measurement}} \quad (4.9)$$

Table 4.22: Initial reading and amount deviation

Degree of rotation, °	Initial reading, (Gauss)	Deviation, (Gauss)
-15	0.33	0.004
+15	0.33	0.012
-30	0.33	-0.010
+30	0.33	0.016
-45	0.33	-0.002
+45	0.33	0.014

As the result in Table 4.22 showing that the AUV initially is in a straight line and the initial reading of magnetometer is recorded. After that, an external force is applied to rotate the AUV in the yaw direction and let the AUV execute yaw correction. When the -15 degree of yaw rotation which is a clockwise rotation until the preset line which indicates the -15° of yaw angle from the straight line in the lab pool. After the manual yaw rotation is done and AUV will automatically detect the angle of the y-axis in magnetometer and rotate back anti-clockwise with a time delay as yaw correction. In the result of yaw correction, as shown in Table 4.22, the deviation of yaw correction is less than ±0.1 gauss which is acceptable to perform the straight line movement for AUV. Besides that, the standard deviation is calculated by using equation 4.5 which is 0.00567 that closed to zero. Thus this indicates that yaw correction able to return the AUV to original position very close.

4.2.7 Experiment 7: Speed Test

Speed test is one of the important tests to evaluate the 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 4.23: Speed test result

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	3.5	0.286	3.7	0.270	3.2	0.313	2.7	0.370
2	6.5	0.308	7.0	0.286	5.8	0.345	4.8	0.417
3	9.1	0.330	9.9	0.303	8.2	0.366	6.8	0.441
4	11.5	0.348	12.7	0.315	10.7	0.374	9.0	0.444
5	14.0	0.357	15.5	0.323	13.3	0.376	10.9	0.459
6	16.4	0.366	18.1	0.331	15.7	0.382	12.7	0.472
7	18.9	0.370	20.7	0.338	18.2	0.385	14.7	0.476
8	21.6	0.370	23.4	0.342	20.7	0.386	16.6	0.482
9	24.4	0.369	26.2	0.344	23.2	0.388	18.6	0.484
10	26.9	0.372	28.7	0.348	25.3	0.395	20.2	0.495

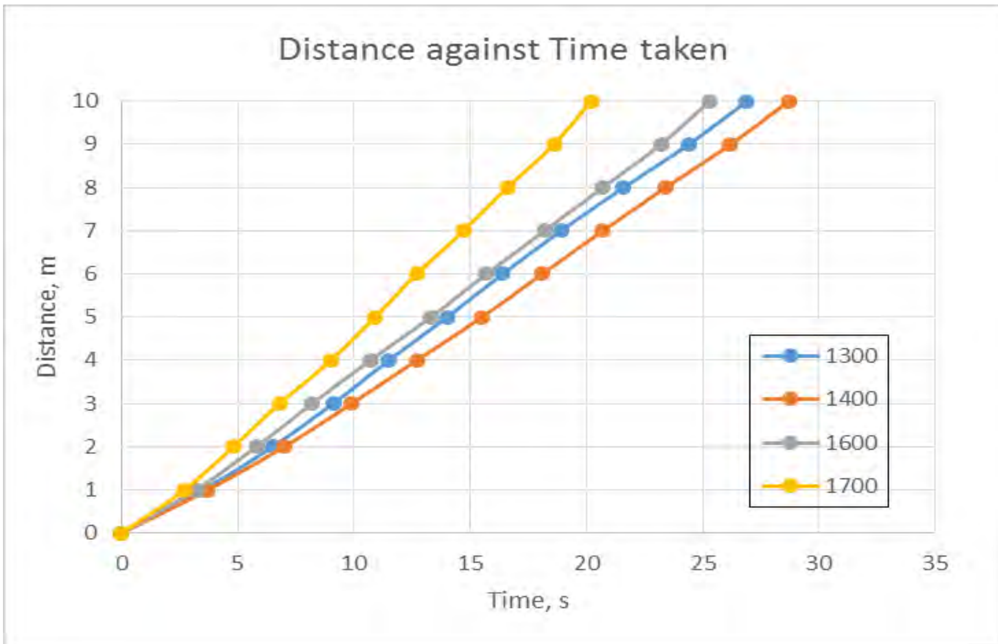


Figure 4.10: Velocity graph of AUV

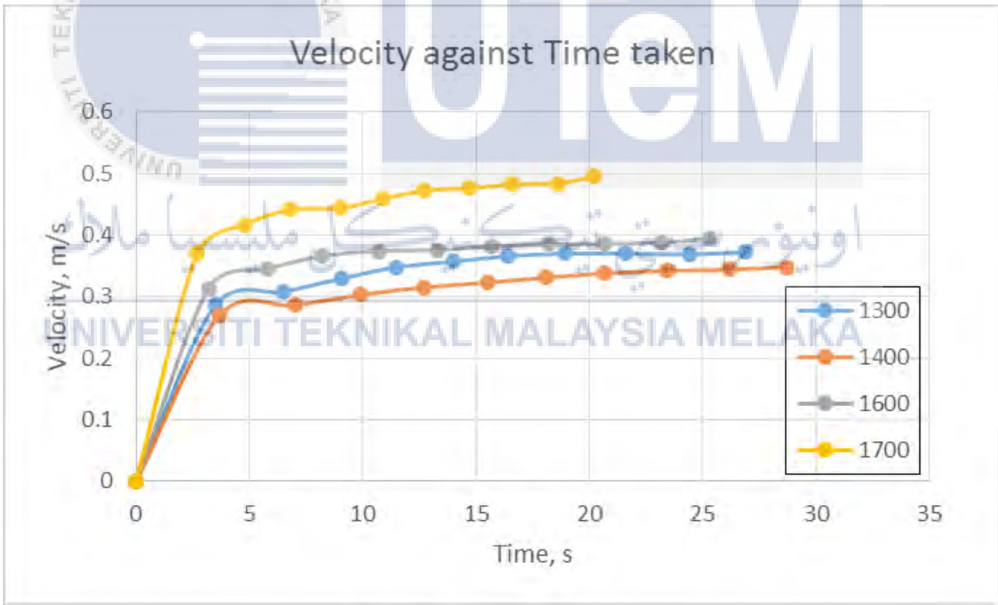


Figure 4.11: Acceleration graph of AUV

The velocity graph for 4 different PWM tests is plotted in Figure 4.10 and acceleration graph is plotted in Figure 4.11. 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 six T100 thrusters to move. This is a major problem for AUV to perform a faster speed in a long period without recharging the battery.

According to T100 documentation, the 1500PWM signal is the zero thrust signal for T100 thruster and the increment from 1500PWM will cause the T100 to thruster in the forward direction while the decrement of PWM from 1500PWM will thrust T100 in reverse direction. In Table 4.23, the AUV moved forward for 10 m distance in 25.3 seconds with 1600PWM and 20.2 seconds with 1700PWM. This shows that using 1700PWM to run the AUV will save 5.1 seconds to complete a 10 m distance in the forward direction. The AUV move with increasing speed when the AUV is turned on. Both PWMs show the speed increases as AUV moving further due to the inertia of AUV decreases. Based on Figure 4.10 and 4.11, both the velocity and acceleration graphs show that 1700PWM has the steeper slope which is greater gradient than 1600PWM. As the forward PWM of T100 thruster increases, the velocity of AUV increases and has a higher acceleration.

For the same table, the AUV moved in a reverse direction for 10 m distance in 28.7 seconds with 1400PWM and 26.9 seconds with 1300PWM. By using 1300PWM to run the AUV will save 1.8 seconds to complete a 10 m distance in reverse direction. The AUV required more time to push it moved in reverse direction compared to forward direction due to the design of T100 thruster. Based on Figure 4.10 and 4.11, both the velocity and acceleration graphs show that 1300PWM has the steeper slope which is greater gradient than 1400PWM. As the backward PWM of T100 thruster decreases, the velocity of AUV increases and has a higher acceleration.

4.2.8 Experiment 8: Turning Test

AUV was tested to find out its speed to move left and right in the swimming pools. The AUV applied with different PWM throughout the whole experiment to turn in 90° right and left which is a combination of the different direction of thrust between left thrusters and right thrusters. This combination of different of PWM will produce a good rotation on the water and reduce the drifting of AUV during the underwater rotation.

Table 4.24: Turning right speed test in swimming poll

Thruster PWM		Time taken to turn right, s			
Left	Right	1^{st}	2^{nd}	3^{rd}	Average
1600	1400	6.1	5.7	6.1	6.0
1650	1350	5.3	5.2	5.5	5.3
1700	1300	5.0	5.1	5.0	5.0
1750	1250	4.2	4.7	4.2	4.4
1800	1200	3.2	3.8	4.0	3.7

Table 4.25: Turning left speed test in swimming poll

Thruster PWM		Time taken to turn left, s			
Left	Right	1^{st}	2^{nd}	3^{rd}	Average
1400	1600	6.2	5.9	6.3	6.1
1350	1650	5.6	5.7	6.0	5.8
1300	1700	5.1	5.0	5.4	5.2
1250	1750	4.5	4.6	4.4	4.5
1200	1800	3.9	4.1	4.1	4.0

For both tables, the time taken for AUV to turns in left and right decreases as the speed of thruster increase in direction. There is about a bit faster between turn right compare to turn left due to wind and water wave at swimming pool. This turning speed test concluded that it's able to function well under the water. If the AUV required to turns right, then the right thruster move in reverse direction while the left thruster will move in forwarding direction and vice versa.

4.2.9 Experiment 9: Straight Line Moving Test

AUV is tested in the swimming pool to complete the straight line moving task with different distance. Table 4.26 shown that the result of AUV to pass through the gate with 10 repeated test for each distance.

Table 4.26: Straight Line Gate Test

Distance, m	AUV pass through the gate									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
5	√	√	√	√	√	√	√	√	√	√
6	√	x	√	√	√	√	√	√	√	x
7	√	√	√	√	x	√	√	√	√	√
8	√	x	√	√	√	x	√	√	√	√
9	x	√	√	√	x	√	x	√	√	√
10	x	√	x	√	√	√	√	√	√	√

As the result shown that AUV is able to perform the straight line task perfectly in 5 meter distance from the starting zone without any mistake. Furthermore, the result for the 6 meter until 8 meter gate test which is at most 2 mistake out of 10 tries which is about 80 percent or higher chance to pass through the gate below the range less than 8 meters. For the further distance which is 9 meters has 3 mistake which is because the yaw correction is having some limitation when the water wave is too strong under the water and cause the sensor unable to return the AUV to the correct direction. Lastly, the 10 meter test is successfully complete the gate task in 8 tries out of 10 tries.

4.3 Summary

Overall, Chapter 4 discussed the results obtained from the analysis in SolidWorks and also experiments. The analysis done in SolidWorks included the 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 AND FUTURE WORK

5.1 Conclusion

As a conclusion, the outline of Autonomous Underwater Vehicle (AUV) base on the BlueROV is testing and energized. This task is to design and manufacture the AUV parts is successfully done. This project focuses on the design and fabricates the AUV in mechanical as well as an electrical part with coding. Before beginning the undertaking, gathering data and thought from different sources is imperative. To start with, the different design of AUV in the article was being studied and get the thought until the finished plan is affirmed after change and change in Solidworks. The settled plan will then experience investigation, for example, stress and strain test and center of mass. The investigation on the Solidworks gives more insights about the AUV when the outline is tried in a genuine circumstance.

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 assembly 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. Besides, AUV's movement performance shows in the speed (0.395m/s), depth (1m) and turning (6s) tests with a few data as a reference. As a result, all data collected in the experiments were considered accurate and precise.

5.2 Future work

In future, the student can design a proper waterproof wire port from the hull to ay computer and keep the circuit to prevent short circuit due to water leakage. This reduces the time taken when exchanging the Arduino coding and also easy for data collection. Besides that, more axis gyroscope from the IMU sensor can be implemented into the AUV to more accurate yaw correction. Next, the research for sensor include the hydrophone and sonar should be focused since AUV required better electronic parts for higher performance. In a conclusion, controller in an embedded system can be designed to improve the robustness and stability of the prototype. For example, besides fuzzy logic controller, the artificial neural network can be introduced into the depth control algorithm and tilting algorithm. As a future work, the proposed methods can be more accurate through more real-time experiments.

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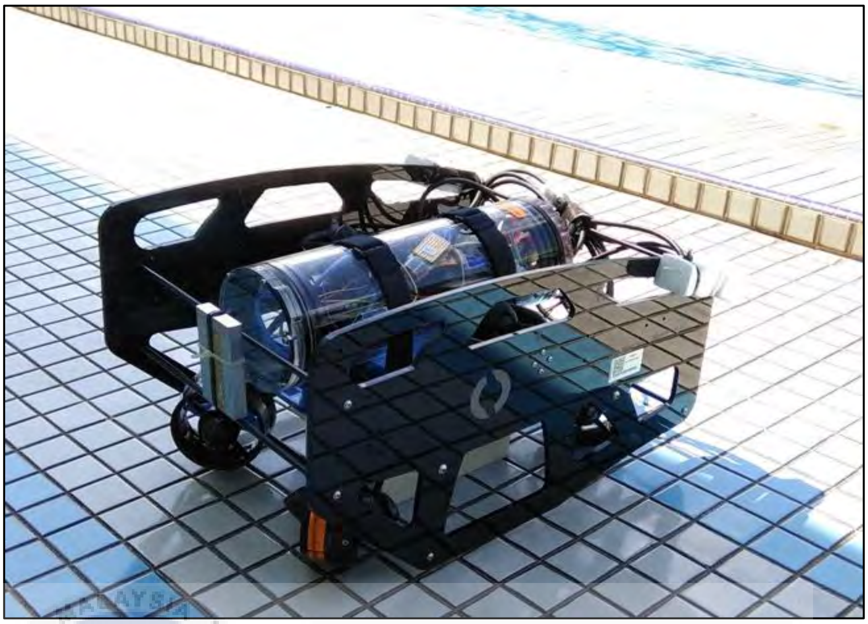
APPENDIX A: Gantt chart

Project Activites FYP 1	Week													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Identify the project title	■													
Identify project objective with supervisor	■	■												
Literature review			■	■	■									
Methodology outline					■	■								
Prototype design in Solidworks						■	■	■						
Finalize final design in Solidworks							■	■						
Performace analysis in Solidworks								■	■					
Design of experiment procedure								■	■	■				
Data collection and analysis										■	■			
FYP 1 presentation											■			
FYP 1 report writing											■	■	■	■

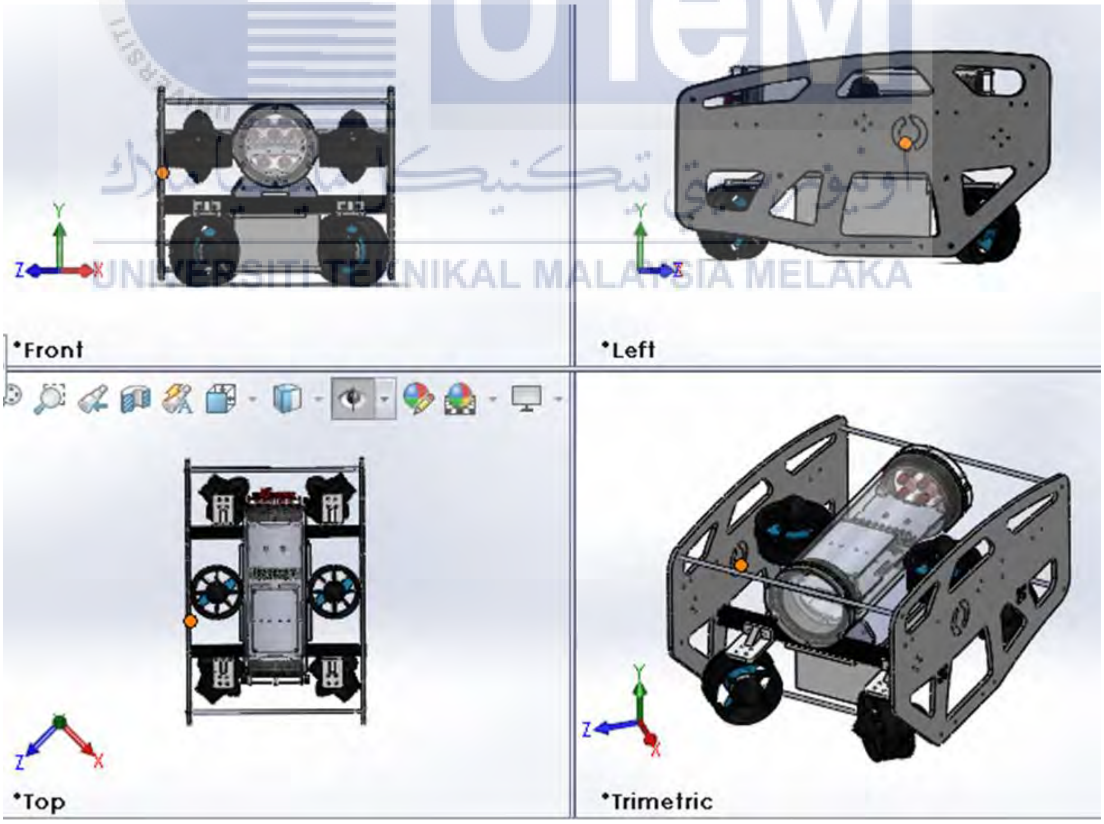
Project Activities FYP 2	Week													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of material	■													
Purchasing of material		■												
Programming			■	■										
Assembly for hardware					■	■								
Experiment test in lab and pool							■	■	■					
Data collection							■	■	■					
Data analysis										■	■			
System troubleshooting											■	■		
Further improvement												■		
FYP report writing												■	■	■

APPENDIX B: Properties of UTeM AUV



Name	UTeM AUV
Dimension	42.28cm X 55.48cm X 42.56cm
Weight	8.67 Kg
Speed	0.395 m/s (1600PWM)
Depth	3 meter (Limitation of swimming pool)
Mechanical Part	Acrylic frame, PLA enclosure box, BlueRobotics T100 thruster, polystyrene
Electrical Part	12V battery, 9V battery, Arduino UNO, GY80 IMU sensor, MPX5700AP, ESC30A

APPENDIX C: Solidwork View of AUV Assembly



APPENDIX D: Arduino Coding for Depth Control

```
#include <Servo.h>
Servo servo5;
Servo servo6;
unsigned long timer = 0;
float timeStep = 0.01;
void setup() {
Serial.begin(9600);
servo5.attach(10);
servo6.attach(11);
delay(1000); }
void loop() {
timer = millis();
float voltage = analogRead(A1);
float pressure=((voltage/1024.0)-0.04)/0.0000012858;
Serial.println(pressure);
delay(10);
Serial.println(voltage);
Serial.println(timer);
delay(10);
if (timer >= 160000 ){
Serial.println("Stop");
servo5.writeMicroseconds(1500); // Send signal to ESC.
servo6.writeMicroseconds(1500); // Send signal to ESC.
delay(10000); }
if (voltage <= 177) {
Serial.println("SUBMERGE DOWN");
servo5.writeMicroseconds(1580); // Send signal to ESC.
servo6.writeMicroseconds(1580); // Send signal to ESC.
delay(2000);
servo5.writeMicroseconds(1500); // Send signal to ESC.
servo6.writeMicroseconds(1500); // Send signal to ESC.
delay(1000); }
else if (voltage >187) {
Serial.println("UPWARD");
servo5.writeMicroseconds(1500); // Send signal to ESC.
servo6.writeMicroseconds(1500); // Send signal to ESC.
delay(1000);
}
}
```

APPENDIX E: Arduino Coding for Yaw Control

```
#include <Servo.h>
#include <Wire.h>
Servo servo1;
Servo servo2;
Servo servo3;
Servo servo4;
unsigned long timer = 0;
float timeStep = 0.01;
#define Magnetometer_mX0 0x03
#define Magnetometer_mX1 0x04
#define Magnetometer_mZ0 0x05
#define Magnetometer_mZ1 0x06
#define Magnetometer_mY0 0x07
#define Magnetometer_mY1 0x08
int mX0, mX1, mX_out;
int mY0, mY1, mY_out;
int mZ0, mZ1, mZ_out;
float heading, headingDegrees, headingFiltered, declination;
float Xm,Ym,Zm;
#define Magnetometer 0x1E
void setup(){
  //Initialize Serial and I2C communications
  Serial.begin(9600);
  servo1.attach(3);
  servo2.attach(5);
  servo3.attach(6);
  servo4.attach(9);
  Wire.begin();
  delay(100);

  Wire.beginTransmission(Magnetometer);
  Wire.write(0x02);
  Wire.write(0x00);
  Wire.endTransmission();
}
void loop(){
  thruster();
   timer = millis();
  Wire.beginTransmission(Magnetometer);
  Wire.write(Magnetometer_mX1);
  Wire.endTransmission();
  Wire.requestFrom(Magnetometer,1);
  if(Wire.available()<=1)
  {
    mX0 = Wire.read();
```

```
}
Wire.beginTransmission(Magnetometer);
Wire.write(Magnetometer_mX0);
Wire.endTransmission();
Wire.requestFrom(Magnetometer,1);
if(Wire.available()<=1)
{
 mX1 = Wire.read();
}
Wire.beginTransmission(Magnetometer);
Wire.write(Magnetometer_mY1);
Wire.endTransmission();
Wire.requestFrom(Magnetometer,1);
if(Wire.available()<=1)
{
 mY0 = Wire.read();
}
Wire.beginTransmission(Magnetometer);
Wire.write(Magnetometer_mY0);
Wire.endTransmission();
Wire.requestFrom(Magnetometer,1);
if(Wire.available()<=1)
{
 mY1 = Wire.read();
}
Wire.beginTransmission(Magnetometer);
Wire.write(Magnetometer_mZ1);
Wire.endTransmission();
Wire.requestFrom(Magnetometer,1);
if(Wire.available()<=1)
{
 mZ0 = Wire.read();
}
Wire.beginTransmission(Magnetometer);
Wire.write(Magnetometer_mZ0);
Wire.endTransmission();
Wire.requestFrom(Magnetometer,1);
if(Wire.available()<=1)
{
 mZ1 = Wire.read();
}
mX1=mX1<<8;
mX_out =mX0+mX1;
Xm = mX_out*0.00092;
mY1=mY1<<8;
mY_out =mY0+mY1;
Ym = mY_out*0.00092;
```

```
  mZ1=mZ1<<8;
  mZ_out =mZ0+mZ1;
  Zm = mZ_out*0.00092;
  heading = atan2(Ym, Xm);
   declination = 0.073;
  heading += declination;
    if(heading <0) heading += 2*PI;
  if(heading > 2*PI)heading -= 2*PI;
  headingDegrees = heading * 180/PI;
  headingFiltered = headingFiltered*0.85 + headingDegrees*0.15;
  Serial.println(headingFiltered);
  Serial.print("x:");
  Serial.print(Xm);
  Serial.print("y:");
  Serial.println(Ym);
  delay(50);
}
void thruster(){
delay(10);
if (timer >= 60000 ){
Serial.println("Stop");
servo1.writeMicroseconds(1500);
servo2.writeMicroseconds(1500);
servo3.writeMicroseconds(1500);
servo4.writeMicroseconds(1500);
delay(50); }

if (Ym > 0.31 && Ym < 0.41) {
Serial.println("FORWARD");
servo1.writeMicroseconds(1650);
servo2.writeMicroseconds(1650);.
servo3.writeMicroseconds(1650);
servo4.writeMicroseconds(1650);
delay(2000);
servo1.writeMicroseconds(1500);
servo2.writeMicroseconds(1500);
servo3.writeMicroseconds(1500);
servo4.writeMicroseconds(1500);
delay(50); }
else if (Ym >= 0.42 && Ym < 0.52) {
  Serial.println("turn right");
servo1.writeMicroseconds(1700);
servo2.writeMicroseconds(1650);
servo3.writeMicroseconds(1700);
servo4.writeMicroseconds(1650);
delay(2000);
servo1.writeMicroseconds(1500);
```

```
servo2.writeMicroseconds(1500);
servo3.writeMicroseconds(1500);
servo4.writeMicroseconds(1500);
delay(50); }
else if (Ym >=0.18  && Ym <= 0.28) {
 Serial.println("turn left");
servo1.writeMicroseconds(1650);
servo2.writeMicroseconds(1700);
servo3.writeMicroseconds(1650);
servo4.writeMicroseconds(1700);
delay(2000);
servo1.writeMicroseconds(1500);
servo2.writeMicroseconds(1500);
servo3.writeMicroseconds(1500);
servo4.writeMicroseconds(1500);
delay(50); }
```