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Autonomous Underwater Vehicle

Mechatronic Skripsie Project 478 / 488

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Execution Summary

Title of Project
Autonomous Underwater Vehicle (AUV)
Objectives
To design and implement an AUV using two thrusters for propulsion and one thruster for depth control. Design, implement and test the control algorithms for the AUV, using a Raspberry Pi or any other microcontroller. Also add a "ballast tank", such that the AUV will stay at a specific depth, when all motors are shut off. If time allows, we can passive acoustic sensors to the AUV.
If the project is successful, how will it make a difference?
The success of the project will continue research and development focused on advancing the level of autonomy of the Autonomous Underwater Vehicle. The AUV will then have many applications including use for; military and defence, oil and gas, environmental protection and monitoring, oceanography, archelogy and exploration, search and salvage operations.
What are the risks to the project being successful?
Risks include time constraints, technology and electronic constraints, budget constraints, resource availability, Covid-19 lockdown, and load shedding. The risks are manageable however certain level of risk is accepted within the course of the project.
Why is the project expected to be successful?
The project is expected to succeed because of the thoughtful planning that was done before completing each step of the design procedure which ensures the mitigations of possible and unexpected risks. After the design stage, building and assembling the AUV can take place. Followed by coding and final testing phase.
What contributions have/will other students made/make?
In 2009, R. Busch conducted a thesis report about the modelling and simulation of an autonomous underwater vehicle. R. Busch was the only previous scholar from Stellenbosch University who conducted research on this topic. His work will support this project and the continuation of this topic in the years to come at Stellenbosch University.
Which aspects of the project will carry on after completion?
The AUV can be continually improved by addition of sonar sensors to avoid dolphins and whales. Furthermore, the addition of cameras and more thrusters can be integrated for data collection and increased speed control. Since no cameras will be attached for this project and only 3 thrusters will be used. The code is another aspect that can be developed further to increase the degree of autonomy and the artificial intelligence of the robot. A second ballast tank can be added.
What are the expected advantages of continuation?

The topic is relatively new and therefore can advanced in multiple directions. Sonar detectors or other sensors can be integrated and used as object avoidance. AUV sensors can be included which will simplify the code and ensure precise control over the AUV. The use of Kalman filters can then be integrated using the estimated position equation and the sensors to further increase precision and accuracy. A second ballast tank added to both sides of the chosen design, for increased equilibrium and faster depth control. Improved code will allow for the AUV to accomplish objectives from multiple markets, instead of targeting only one. Cameras will allow additional data to be collected. Additional recommendations are detailed in section 9.1 of this report.
What arrangements have been made to expedite continuation?
All designs and code for this project can be used (as long as referenced) for future projects. The built AUV belongs to Stellenbosch University, future students can then step in the footprints already made rather than make their own. Section 9 and 10 of this report gives additional information about the continuation of research in upgrading and advancing the autonomous underwater vehicle.

ECSA Exit Level Outcomes

ECSA Outcomes Assessed in this report	
ECSA Outcome	**Addressed in Sections:**
ELO 1. Problem Solving: Demonstrate competence to identify, assess, formulate and solve convergent and divergent engineering problems innovatively.	1; 3; 6; 7; 8; 9; Appendix D.
ELO 2. Application of scientific and engineering knowledge: Demonstrate competence to apply knowledge of mathematics, basic science and engineering sciences from first principles to solve engineering problems.	2; 3; 6; 7; Appendix C; Appendix D; Appendix F.
ELO 3. Engineering Design: Demonstrate competence to perform creative procedural and non-procedural design and synthesis of components, systems, engineering works, products or processes.	3; 4; 5; 6; 7; Appendix B; Appendix D; Appendix C; Appendix G.
ELO 5. Engineering methods, skills and tools, including Information Technology: Demonstrate competence to use appropriate engineering methods, skills and tools, including those based on information technology.	3; 4; 5; 6; 7; 8; Appendix A; Appendix E.
ELO 6. Professional and technical communication: Demonstrate competence to communicate effectively, both orally and in writing, with engineering audiences and the community at large.	Project Proposal; Progress Report; Preliminary Draft; Final Report; Oral Presentation; Project Poster
ELO 8. Individual, team and multidisciplinary working: Demonstrate competence to work effectively as an individual, in teams and in multidisciplinary environments.	Demonstrated throughout the report
ELO 9. Independent learning ability: Demonstrate competence to engage in independent learning through well-developed learning skills.	1; 2; 3; 8; 10

Plagiarism declaration

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Date: 20/10/2021 ....

Abstract

This project investigates the design and implementation of an Autonomous Underwater Vehicle (AUV) using two thrusters for propulsion and one thruster for depth control. It further investigates the design, implementation and testing of the control algorithms for the AUV, using an Arduino UNO. The addition of a ”ballast tank” is required, such that the AUV will stay at a specific depth, when all motors are shut off.

This report takes the reader through the process of researching AUVs, identifying market trends, building a conceptual design, identification of components required to build a prototype and then designing the complex motion control algorithms necessary to achieve autonomous motion underwater. The algorithms are modelled in a simulation using MATLAB/Simulink to test its accuracy. The prototype AUV was then built and programmed with the control algorithms, considering the hydrodynamic and hydrostatic impact of being underwater.

The test results of both the simulated model and the actual prototype are evaluated and recommendations are made for future development of the AUV.

Acknowledgements

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List of Symbols

A	Area (m^2)
C_d	Coefficient of drag
FA	Frontal area (m^2) of the AUV
$F_{BUOYANCY}$	Buoyancy force (N)
F_{DRAG}	Drag force (N)
F_{HS}	Hydrostatic force (N) on AUV
F_{WEIGHT}	Weight of AUV (N)
I_{ZZ}	Mass moment of inertia about Z-axis
M_Z	Moment (Nm) about Z-axis
U_1	Thrust force (N) in the body frame X^B direction
U_2	Moment (Nm) rotation about Z^B axis
U_3	Thrust force (N) in the body frame Z^B direction
X_{act}	Actual position of AUV in the earth frame [X-axis]
X_{ref}	Reference input positions for AUV in the earth frame [X-axis]
XYZ_{act}	Actual position of AUV in the earth frame [all 3 axes]
XYZ_{ref}	Reference input positions for AUV in the earth frame [all 3 axes]
Y_{act}	Actual position of AUV in the earth frame [Y-axis]
Y_{ref}	Reference input positions for AUV in the earth frame [Y-axis]
Z_{act}	Actual position of AUV in the earth frame [Z-axis]
Z_{ref}	Reference input positions for AUV in the earth frame [Z-axis]
$\ddot{X}_E$	Acceleration (m/s^2) in the earth frame X^E direction.
$\ddot{Y}_E$	Acceleration (m/s^2) in the earth frame Y^E direction.
$\ddot{Z}^E$	Acceleration (m/s^2) in the earth frame Z^E direction.
a	Acceleration (m/s^2)
g	Gravitational acceleration = 9.81 (m/s^2)
h	Height (m)
m	Mass of AUV (kg)
$\dot{m}$	Rate of change of AUV mass (kg/s)
Ψ_{act}	Actual angle of rotation of AUV about Z-axis

Ψ_{ref}	Reference angle of rotation of AUV about Z-axis
Ψ	Angle of rotation (rad) about Z^B axis
$\ddot{\Psi}$	Angular acceleration (rad/s^2) about Z^B axis
ρ	Density of sea water = 1023.6 kg/m^3

Abbreviations

ARCS	Autonomous Remotely Controlled Submersible
AUV	Autonomous Underwater Vehicle
CAGR	Compound Annual Growth Rate
DC	Direct Current
DMFC	Direct Methanol Fuel Cell
DOF	Degree(s) of Freedom
ESC	Electronic Speed Controller
GPS	Global Positioning System
I/O	Input/Output
IDE	Integrated Development Environments
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
PID	Proportional Integral and Derivative
PLA	Polylactic Acid
PWM	Pulse-Width Modulation
RC	Remote Control
ROS	Robot Operating System
ROV	Remote Operated Vehicle
SAUV	Solar-Powered Autonomous Underwater Vehicle
SCL	Serial Clock Line
SDA	Serial Data Line
SLAM	Simultaneous Localisation and Mapping
SMD	Surface Mount Device
SPURV	Special Purpose Underwater Research Vehicle
USBL	Ultra-Short BaseLine
UTP	Underwater Transponder Positioning
VAT	Value Added Tax

1 Introduction

1.1 Background

The concept of underwater vehicles is well documented and various designs and applications have been widely used across the world for decades. These vehicles are largely operated remotely from the surface using a tethered cable for sending control signals to the robot underwater. These underwater vehicles are called ROVs (Remote Operated Vehicles). Whilst the design of such ROVs appear simple, they still are expensive pieces of equipment and range anything from ZAR 30,000 upwards. Recent advances in artificial intelligence and robotics have coined the phrase “autonomous motion” that describes the ability of machines to work by themselves without human intervention. This type of behaviour of autonomous machines is often seen in fictional movies and not readily available as commercial off-the-shelf products. The AUV (Autonomous Underwater Vehicle) is just one type of robot that employs sophisticated control algorithms so that it can achieve kinematic movement without being controlled by a remote human operator. These AUVs should not be confused with ROVs and are rarely available in the commercial marketplace. An example of an ROV can be seen in figure 1 below.

Figure 1: Example of an ROV

This report identifies what an autonomous underwater vehicle is and what is the market demand and applications for this robot. In addition, the report investigates the project's description with further elaboration on the project's objectives, scope, and motivation. The report also describes the design of the robot, while explaining why certain design choices were made. All calculations required to design the control algorithms are attached to the appendices and referred to when appropriate. A technoeconomic analysis of the project is included in appendix E. The report includes the signal and voltage testing of the major electrical component used for the project along with a safety report when recording these measurements. The appendices also include all 3D printed drawings, images of the final prototype and the components list.

1.2 Objectives

This project seeks to design and build an AUV that can be mass produced and marketed as a low-cost commercially available unmanned underwater robot. To achieve this broad aspiration, this project has the following specific objectives: To design and implement an AUV using two thrusters for propulsion and one thruster for depth control. Design, implement and test the control algorithms for the AUV, using a Raspberry Pi or any other micro-controller. The addition of a "ballast tank" is required, such that the AUV will stay at a specific depth, when all motors are shut off. If time allows, passive acoustic sensors can be added to the AUV.

1.3 Motivation

This project is motivated by needs within the South African oceanographic research and exploration fraternity to assist with their studies of marine life and its evolution across the coastline. As there are great strides made in the field of autonomous motor cars, this project is also motivated by the need to provide similar resource capabilities for underwater exploration. The University of Stellenbosch always seeks to pioneer research and development in applications that take us to the extreme edges of science and technology and this project will be one stone thrown in that direction.

1.4 Scope

The scope of this project is focused on design of control algorithms for autonomous control of thruster propulsion of underwater vehicles. This can be misunderstood to include autonomous navigation of the AUV which is a broad and complex research challenge on its own.

- AUV is designed to be autonomous and not be operated with a remote tether cable and joystick.

- Controller – PID controlled thrusters and ballast tank.

- The AUV kinematics and its control system is built on MATLAB Simulink, implemented on Arduino IDE, and uploaded to an Arduino UNO. Physical testing was be conducted in swimming pool.

- Low-cost materials were used, and design limitations have been noted after testing is completed.

- Excluded from scope – Obstacle avoidance, SLAM (Simultaneous Localisation and Mapping) navigation, and ROV tether-cable control.

2 Literature Review

2.1 What is an Autonomous Underwater Vehicle?

The AUV is just one type of robot that employs sophisticated control algorithms so that it can achieve kinematic movement without being controlled by a remote human operator. AUVs are primarily used in a scenario where it is not possible to use a manned vessel or ROV. This is usually due to lack of the adequate equipment, low budget, and crew safety (Busch, 2009). An example of an AUV can be seen in figure 2.

Figure 2: Example of an AUV

Note: figure 2 is not the AUV in this project.

2.2 History of AUVs

The first robot that can be classified as an AUV was implemented in 1957 and designed by Stan Murphy and Bob Francois at the University of Washington. According to Gafurov the first AUV was named SPURV (Special Purpose Underwater Research Vehicle). The SPURV design had a torpedo shape and was made of aluminium and screw driven. In 1957 there were no microcontrollers to control the AUV, so Murphy and Francois used acoustic communications, which is a method of sending and receiving signals in an aquatic environment. The AUV proved as a reliable device and was favourably used for oceanography research until 1979. After the success of SPURV, the University of Washington continued their research and development of unmanned underwater vehicles. After modifications and upgrades to SPURV from the engineers at the University of Washington, the release date of SPURV II happened in 1973. SPURV II was successfully used till the 1980s.

An AUV called Scat was created in 1974 by Engineers from the Institute of Automation and Control Processes. After additional upgrades and modifications to Scat, AUVs L-1 and L2 were created. L-1 was used for testing and developing new technologies for the AUV, L-2 - for oceanographic research (Gafurov, 2015).

The ARCS (Autonomous Remotely Controlled Submersible) was the next major AUV created. It was developed in 1983 by a company called ISE Ltd. However, the first voyage only took place 5 years later. ARCS used a 32-bit processor, this allowed users to control and observe the device in real time in addition to staying under water for extended periods of time. ARCS greatest strengths were its new global positioning system, algorithms missions and new power supply.

In 1998 the first solar autonomous underwater vehicle was created by the Russian Institute of Marine Technology Problems called SAUV (Solar-Powered Autonomous Underwater Vehicle). After further research, modifications and upgrades, researchers from AUSI created SAUV-II in 2003.

As the 2000s began, the utilization of AUV technology for a number of commercial tasks became clearer. The AUV was then designed and programmed to accomplish these commercial tasks to produce income for the architects and engineers. There were some technological shortcomings which lead to question how viable economic wise the AUV was in the 2000s.

The AUV is known as commercial product whose demand is increasing rapidly in today’s tech-driven society. Majority of the technological problems experienced in the past decades have been corrected. Allowing for new engineers to build on the intelligence of the AI program and design of AUVs.

2.3 Market and Application

In the world today, the market is rapidly increasing for AUVs. According to MarketsandMarkets, the AUV market is expected to grow from USD 638 million in 2020 to USD 1,638 million by 2025; it is expected to grow at a CAGR (Compound Annual Growth Rate) of 20.8 from 2020 to 2025. This can be seen in the figure 3 below.

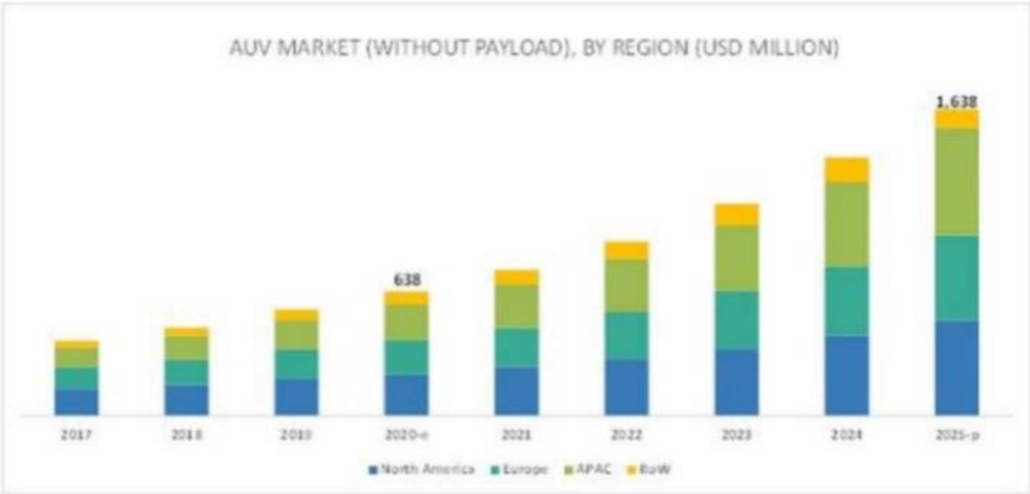

Figure 3: Bar graph depicting the demand for AUV by region (MarketsandMarkets, 2021)

The highest demand is for military and defence such as border security and surveillance, antisubmarine warfare, monitoring of illegal goods, environmental assessment, and mine countermeasures. The second highest demand for AUVs is located in the oil and gas industry. Where they will be used for pipeline surveys, geophysical surveys, debris/clearance surveys, baseline environmental assessments. AUVs are also wanted for environmental protection and monitoring. AUVs are used for habitat research (such as for whales and dolphins), water sampling, fishery study and emergency response. Other applications include oceanography, archaeology and exploration and search and salvage operations. However, there have been cases of AUVs used for illegal activities such as illegal drug traffic.

2.4 Dynamics of an AUV

An Autonomous Underwater Vehicle (AUV) in an environment model experiences hydrostatic forces (and moments) when submerged and hydrodynamic forces (and moments) when moving. The hydrodynamic forces are a fluid's resistance when an object moves through it (Kiseleb, 2017). In a vehicle model the propulsion forces and moments are considered. An AUV should be able to withstand an increase in the environmental model's forces as depth increases in order to record data and structure overhaul at great depths. The main forces acting on the vehicle are buoyancy, weight, drag, lift, and thrust. All of these forces induce moments on the AUV. The vehicle also experiences rotational motion in 3 directions. The rotational motion is roll (x-axis), pitch (y-axis) and yaw (z-axis). Along with the rotational motion, the vehicle also experiences translational motion which are:

surge (x-axis), sway (y-axis) and heave (z-axis). Figure 4 illustrates the 6 degrees of freedom in a clearer way.

2.5 Design

2.5.1 Sensors

It is common that AUVs that are designed and implemented in the industry are accompanied with sensors. These are used to allow the vehicle to autonomously traverse through the ocean. Some sensors allow for the AUV to track data of features in the ocean. Sonar sensors are used to detect objects and animal-life to allow the AUV attain object avoidance. AUVs used in the industry and for commercial use usually have a combination of sensors to increase efficiency and feedback. According to Elias the sensor packages can include video (or cameras) sonar, magnetometers, fluorometers (chlorophyll sensors), dissolved oxygen sensors, conductivity, temperature, and depth sensors (CTDs), pH sensors, and turbidity (suspended sediment concentration) sensors. In this section it is obvious that the more sensors incorporated onto the AUV the higher the real time navigation accuracy. However, realistically these sensors are expensive and are most commonly used for AUVs used in major industries.

2.5.2 Communication and Navigation

AUVs are particularly hard to keep track of underwater as it is known that radio waves can't penetrate through water very far. Therefore, all GPS (Global Positioning System) communication will be lost as soon as the AUV submerges. Dead reckoning is a common method used to track and manoeuvre an AUV underwater. It is the process of estimating the current location of a traveling body by using a previously determined location, it also integrates an estimated velocity, direction, and running time. Dead reckoning is also the most cost-effective method to navigate the AUV, however the disadvantage is that the AUV may not be able to avoid obstacles and marine life. An inertial navigation system (INS) is usually selected as the core navigation equipment for AUV navigation because it never fails to measure (Bao, 2020). The INS problem comes with the AUV travelling long distances as the intrinsic error of INS sensors accumulates with the elapsed running time of the vehicle. Another method includes using an ultra-short baseline (USBL) positioning where the AUVs position is calculated using the last known GPS location of the AUV. The USBL method incorporates the use of sound measurements and orientation of the AUV. According to Bao the INS can be coupled with an underwater transponder positioning (UTP). This is beneficial as it increases the navigation accuracy achieved by aiding both the INS and the USBL.

2.5.3 Propulsion

AUVs have a couple of propulsion systems available. The propulsion system either use a brushless or brushed DC motor for the thruster. According to McMillan brushless motors are more efficient and durable than brushed motors. However, brushed motors do not require an electronic speed controller (ESC) making it the more cost-effective option. The best option is still the brushless motors, as over the years the price for ESCs have decreased. The propulsion system further contains a propeller with or without a nozzle and a lip seal. The nozzle is used to reduce the amount of noise produced by the thrusters. The lip seal ensures that the internal electronics of the thrusters are completely waterproof. Majority of advanced AUVs have more than three thrusters to complete the propulsion system, this enables control over more if not all degrees of freedom. Advanced AUVs also contain a secondary shaft seal system in case of a lip seal failing during operation.

2.5.4 Power

Majority of AUVs today make use of rechargeable batteries as the main core power supply. There are a variety of batteries that can be used such as lithium-ion, lithium polymer, nickel metal hydride, semi fuel cell, DMFC (Direct Methanol Fuel Cell) and photovoltaic solar power (Hasvold, 2006). Most commonly used battery pack for an AUV is the lithium-ion batteries, as the lithium-ion cells have been established as a trustworthy and consistent energy source for the vehicle. There are a few AUVs that use an aluminium semi-fuel battery pack, but these batteries are not eco-friendly due to the extensive waste produced, they also require extensive maintenance and are costly to recharge.

3 Concept Design

3.1 Background

The design of the control system for the AUV started out as a simplified view of a complex machine meant to traverse underwater. Initially, it was envisaged to layout the thrusters and then proceed to install electronic sensors to capture real-time motion of the AUV and feed that back to a controller that would navigate the robot to a defined reference position in 3D-space.

However, this simplified approach was met with the harsh reality that underwater sensors to achieve the above are not readily available in the market – cheap sensors are unreliable (e.g., IMU drift) and specialised sensors such as sonar and underwater GPS systems are very expensive. Underwater systems also have much degradation in accuracy compared to operating on land or air, for example GPS and Wi-Fi signals are largely affected by the refractive properties of water.

The next challenge encountered during the early stages of design, see figure 4 was that the AUV really is a 6-DOF (degree of freedom) system, meaning that whilst it translates in 3D-space along the XYZ axis, it is possible that the AUV simultaneously rotates about each of the XYZ axis. To control these body motions, complex control systems are needed, and more thrusters are required to have total control of the AUV's 6-DOF (Priyadarsini, 2020).

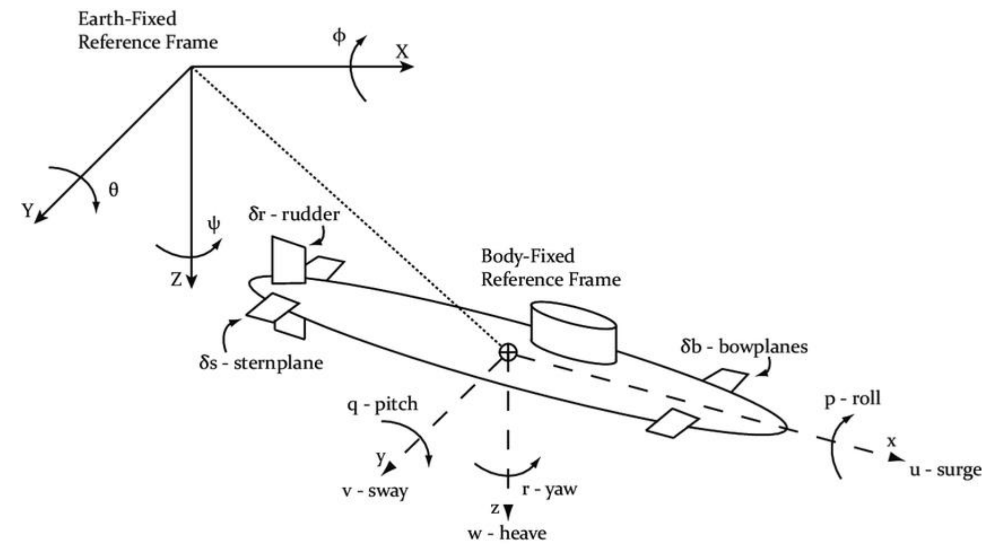

Figure 4: Earth Frame [XYZ] and Body Frame [xyz] of an underwater submarine

The other challenge in modelling the control system for the AUV is that the reference position (where do we want the AUV to go?) is specified in the fixed Earth/Inertial Frame (XYZ axis) whilst the sensors attached to the AUV measure its motion with respect to its own body frame (xyz axis). Therefore, the complexity of the control system is even greater when computations are needed to translate from the AUVs body frame to the Earth's inertial frame.

So finally, the ultimate test to prove the control systems design works properly, is to specify a target reference in the earth's inertial frame [XYZ], say move 5m in X, 3m in Y and 4m deep (Z) and track if the AUV can control its thrusters to move its body frame [xyz] to the desired target.

For this task it was necessary to model a position controller with the AUV's thruster layout and combine it with environmental forces impacting the motion underwater.

3.2 Design Decisions, Limitations and Assumptions

3.2.1 Design Decisions

The AUV project scope is limited to using just three thrusters. Two thrusters for propulsion and one thruster for depth control. Based on the strategic positioning of the thrusters, one can influence the number of degrees of freedom that can be directly controlled. However, with just three thrusters available, it is not possible to control all 6-DOF of the AUV. Some design choices needed to be made and this decision then determined the design of the control system that followed. The following considerations (seen in figure 5) were made in the placement of the thrusters.

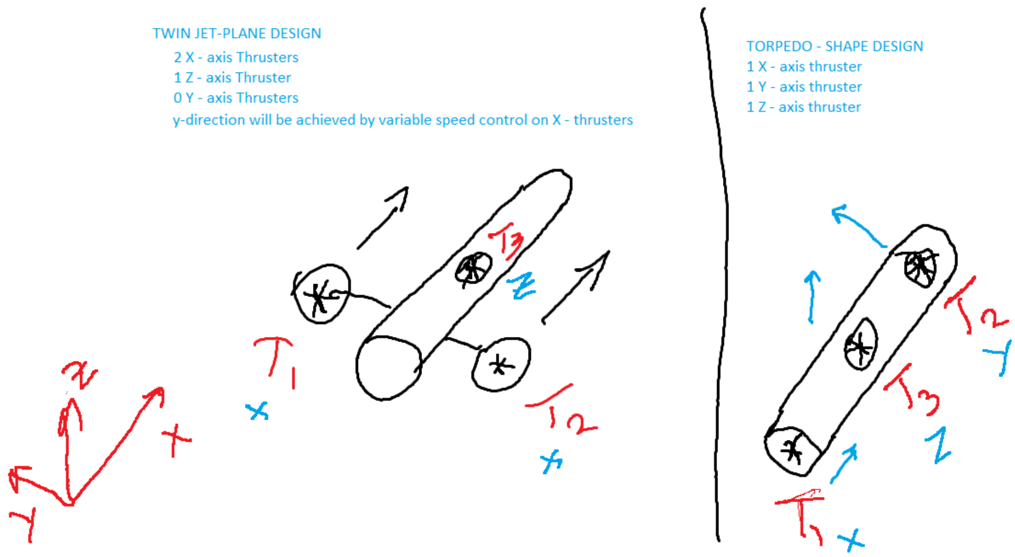

Figure 5: Airplane Vs Torpedo design shape and thruster layout options

The jet plane shape was compared to the torpedo shape. For the jet plane two thrusters are placed on each side (left/right) of the AUV for forward propulsion and one thruster in the middle for vertical (depth) control. The control system would have been easier to design if the torpedo shape was selected. However, in practice, the motion along the body frame y-axis would be largely impeded by the effect of water drag along the y-axis. There are many torpedo-shape designs of AUVs and ROVs in the market, but most have just one main thruster at the rear and use motorised fins to manoeuvre through water. This project scope specifies the use of three thrusters.

In discussions with the Project Supervisor, it was decided to select the “jet plane design” layout for the location of the propulsion thrusters. This means the AUV has two forward-facing (X-axis) thrusters and one vertical-positioned (Z-axis) thruster for depth control.

The three thrusters are located along the mid-point of the AUV portal frame. This helps keep the centre of gravity to the midpoint and aid with stabilising the AUV during vertical motion for during dept change. To turn left or right both thrusters are operating in opposite directions to speed up the turn and keep the AUV turning on the Z-axis. Figure 6 below shows the design of the finalised selected concept design.

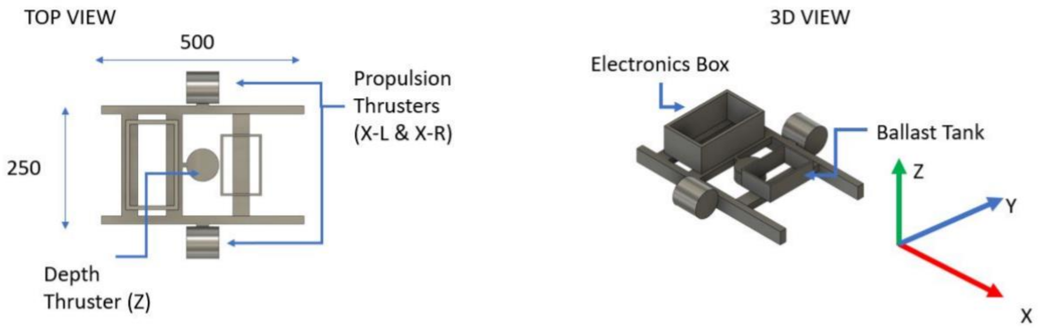

Figure 6: Final concept design

3.2.2 Limitations

The following limitations are noted for the control systems design:

a) The thruster layout only allows direct control 4 degrees of freedom, namely XYZ for translational motion and Yaw-angle (psi ψ) for rotation about the Z-axis.

b) There is no direct control of the pitch and roll of the AUV as there are no thrusters installed to compensate movement for these degrees of freedom.
c) As a mitigating measure for (b) above, stabilising fins were 3D printed and installed on the AUV (can be seen in appendix C). These allow for static and dynamic stability and are not related to the control system algorithm.
d) The ballast tank operates independent of the control system for the thrusters. It only is meant to stabilise the AUV at a constant depth when all thrusters are switched off. This means that the ballast tank does not contribute to the controller's design in going to a target depth specified in the position controller. This is achieved by the depth (Z) thruster.

3.2.3 Assumptions

The following are assumptions made for the design:

a) The AUV can be used in normally calm water as the inability to control pitch and roll effects on the AUV is not built into the control systems design due to insufficient thrusters.
b) If used in adverse underwater currents that affect pitch and roll then the calculations for motion of the distance travelled may be affected and incorrect trajectories may occur.
c) The control system may not recover if the AUV capsizes, and the motion controller can result in absurd trajectories.
d) The Inertial earth frame [XYZ] and AUV body frame [xyz] are aligned at each launch mission. This means that if a target location of XYZ is specified, then at the launch of the AUV, the control system expects that the user places the AUV's nose [x] in the same direction of [X].
e) The AUVs physical design results in close to neutrally buoyant structure and that its centre of mass/gravity and its centre of buoyancy is centralised on the machine. This is an important assumption for the control system design as it means that when the AUV reaches its target reference position, the thrusters can be switched off. If the AUV is not neutrally buoyant then it will either sink or rise when it reaches its goal location. The ballast tank is intended to compensate maintaining the depth when the goal location is reached, since the motion controller is designed to switch off the thrusters. Since the ballast tank has limited capabilities, it will not work properly if the AUV is not close to being neutrally buoyant.

4 System Description and Components

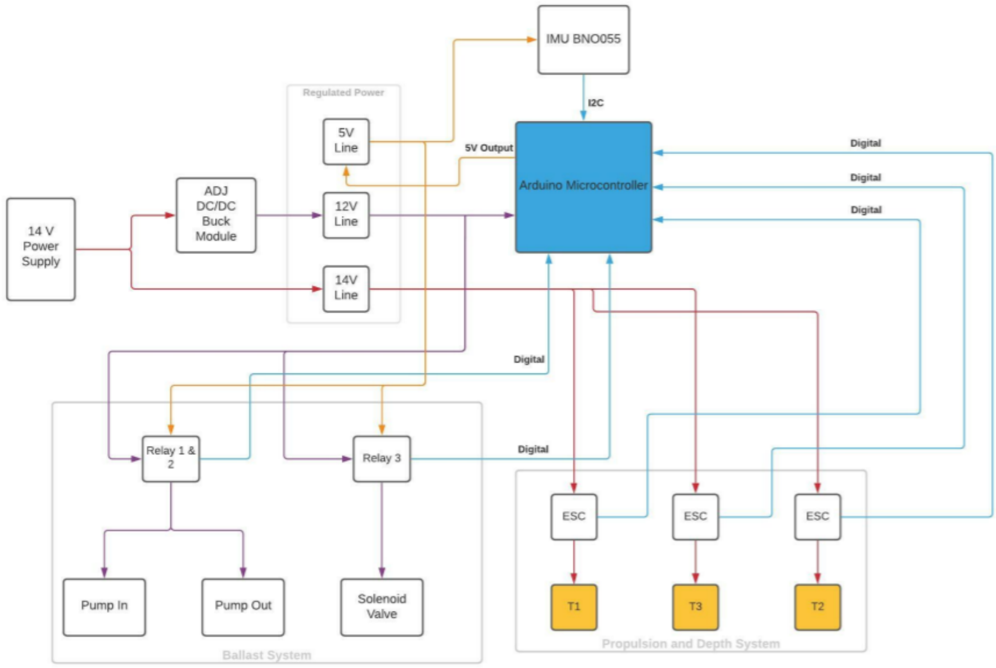

Figure 7: System block diagram

This section covers the various components needed for the AUV project and how they are connected to build the AUV prototype. Testing and signal measurements of the Arduino and power lines is attached to appendix B.

4.1 Microcontroller

The microcontroller used in this project and seen in figure 7 is the Arduino Uno, it is board based on the ATmega328P. It is constructed on the Arm CortexM3 32-bit RISC core operating at a 16MHz frequency. It has high-speed embedded memory with 32KB of flash memory and has SRAM up to 2.2KB. The device operates from a 7 to 12V power supply (therefore voltage regulators are required to step down the 12V power source to a suitable voltage for the microcontroller). Although the operating voltage of the Uno ranges from 6-20V. However, if the Uno is supplied with less than 7V then the 5V output pin may not produce 5V. The device contains 14 digital I/O pins (only 6 produce PWM output) and 6 analog input pins. The microcontroller is the heart of the system (acts like the operating system of the device). It contains the code/software written on Arduino IDE that controls the behaviour of the AUV. The Arduino's 5V output pin is used to create a 5V regulated power supply line.

4.2 IMU BNO055

The IMU (Inertial Measurement Unit) acts as a gyroscope, the device measures the orientation of the device relative to the Earth's axis. The accelerometer transmits digital data that can be read and used using an I2C setup on the Arduino IDE. The frequency limit for I2C communication is 800Hz for the IMU. Two lines are needed for communication for I2C; a SCL (Serial Clock) line and an SDA (Serial Data) line. The SCL and SDA lines are linked to all devices on the I2C bus. The SDA is used to send and receive data while the SCL carries the clock signal. The INT pin on the BNO055 is an HW interrupt output pin, which can be configured to generate an interrupt signal when certain events occur like movement detected by the accelerometer, etc. The voltage level out is 3V. The BNO055 requires an input voltage of 5V DC which is provided by the Arduino Uno 5V output pin as seen in figure 5.

4.3 LM2596 Adjustable DC/DC Buck Module

This device requires an input DC voltage of 4-40V and can generate an output DC voltage of 1.25-37V. The device is supplied with 14V DC and produces an output voltage of 5V DC. The output current for stable operation is 2A. The adjustable DC/DC buck module experiences an internal oscillation frequency of 150KHz and has a large area of copper on its back to enhance heat dissipation. The device makes use of a three digit display so both the input and output voltage can be monitored. The output voltage can be adjusted by tightening/loosening a screw on the potentiometer.

4.4 Relays

The relays used in this project are the two-channel level trigger optocoupler relay module. The use of a two-channel relay simplified the circuit and the wiring of hardware. The module uses genuine quality relay, normally open interfaces. It uses a SMD optocoupler isolation and driving ability to provide a stable performance. The module can be high or low by a jumper setting trigger. Fault-tolerant design, even if the control line is broken, the relay will not operate. The power indicator (green), the relay status indicator (red). The interface design of human nature, all interfaces are available through a direct connection terminal lead, very convenient.

4.5 Submersible Pumps

The pumps used for the AUVs ballast tank are two DC ultra-quiet brushless motor submersible pool water pumps. The flow rate for the pumps is 240 L/hour (4 L/min) . The max head (lift height) is 3m. The maximum rated current is 350mA with a rated voltage of 12V. The pumps also produce a noise level of less than 40dB and have a life span of more than 30000 hours. The weight of each pump is 0.3kg and the dimensions are 10x7x7cm. The pump is not bidirectional and therefore a second pump is used to complete the ballast tank.

4.6 Thrusters

The thrusters selected for this project are three 12V-24V underwater thruster brushless motor propellers for RC boats and AUVs. The thrusters are bi-directional, and dimensions can be seen in the figure 8. The housing for the thrusters is made of PLA (polylactic acid) nylon. The power consumption for each thruster ranges from 100-300W and the maximum current that can be drawn is 17A.

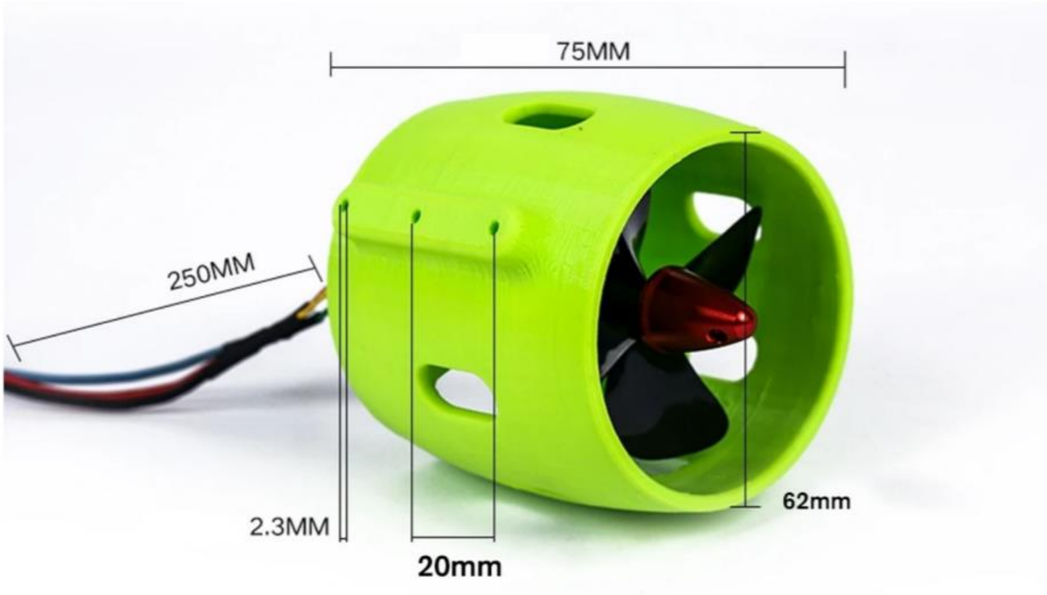

Figure 8: AUV thruster dimensions

4.7 Electronic Speed Controller

ESCs (Electronic Speed Controllers) are used to power and control the speed of the thrusters for the AUV. The ESCs used for this project are the ZMR 20A/30A bidirectional brushless ESC for remote control car pneumatic underwater propellers. There is a total of three ESCs for the project one for each thruster. The

ESCs can draw up to 30A and require at least 12V DC supply. The ESC comprises a wire for: voltage in, ground and signal. The voltage in is connected to the 14V power line, the ground wire goes to ground, and the signal is connected to the desired digital output pin on the microcontroller. The PWM input signal sent through to the ESC controls the thrusters.

4.8 Solenoid Water Valve

The solenoid water valve chosen for the AUV is a CWX-15 DN20 two-way DC motorized brass ball valve. The valve has a rated voltage of 12V DC and uses less than 2W when operating. It also has a working current of less than 80mA. The maximum working pressure for the valve is 1MPa and can produced a maximum torque of 2NM. The material used is brass for the valve body and engineering plastics for the actuator. The opening or closing time of the valve is 5 seconds. The environment temperature for the valve is limited between -15 to 50 °C, while the temperature of the fluid flowing through the valve may not exceed 80 °C and not go below 0 C.

The reason why the solenoid valve is needed for the project is explained in section 7 where the Ballast Tank design is described in depth. In essence the ballast tank works with small 12V DC pumps and the solenoid valve is used to open/close water flow into/out of the Ballast tank such that the water level in the tank does not change when the pumps/ballast is switched off.

5 Hardware Design and Implementation

5.1 Propulsion

5.1.1 Thrusters

There are a total of three thrusters mounted on to the device, two for propulsion and one for depth. All three are a 12-24V underwater thrusters with a brushless motor propeller used for RC boat bait tug and for AUV Robot thrusters. These thrusters were chosen as there are cost-effective and beneficial to the project's budget. A single thruster costs seven times less than the T200 thruster sold by Blue Robotics. However, thrusters selected operate on the same ESC (Electronic Speed Controller) PWM input value as the Blue Robotics thrusters.

The nominal operation for these thrusters is 12-16V, this is recommended for the best balance of thrust and efficiency. The diagram below depicts the thruster's performance by showing the thrust force associated with each ESC PWM input value. If a PWM input value of 1500 is sent the thrusters will stop, if the PWM input value is above 1500 the thrusters will go forward and vice versa for an input value below 1500 (thrusters will reverse). Note that the thrusters can draw a maximum of 23A. Since the thrusters bought are not Blue Robotics thrusters and are rather cost-effective thrusters were selected, the values may differ slightly even though both thrusters operate on the exact same PWM input signal. This can be seen in the figure 9.

5.1.2 Electronic Speed Controller (ESC)

The ESCs control the thrust force produced by the motor by varying the PWM input signal sent via the Arduino. The graph in figure 9 depicts the corresponding thrust force produced by the thruster as a function of the ESC input signal. The graph depicting current drawn from the thruster as a function of the ESC input signal sent is shown in figure 8. For both figures 9 and 10 the project uses the 14V line (the green line, also indicated by the red arrow) to gauge thrust force and current drawn. Figure 11 shows how, the thrusters are connected to the power supply, Arduino, and the ESC. The yellow wire from the ESC in figure 11 is connected to a digital pin on the Arduino to send the PWM input signal to control the thrusters.

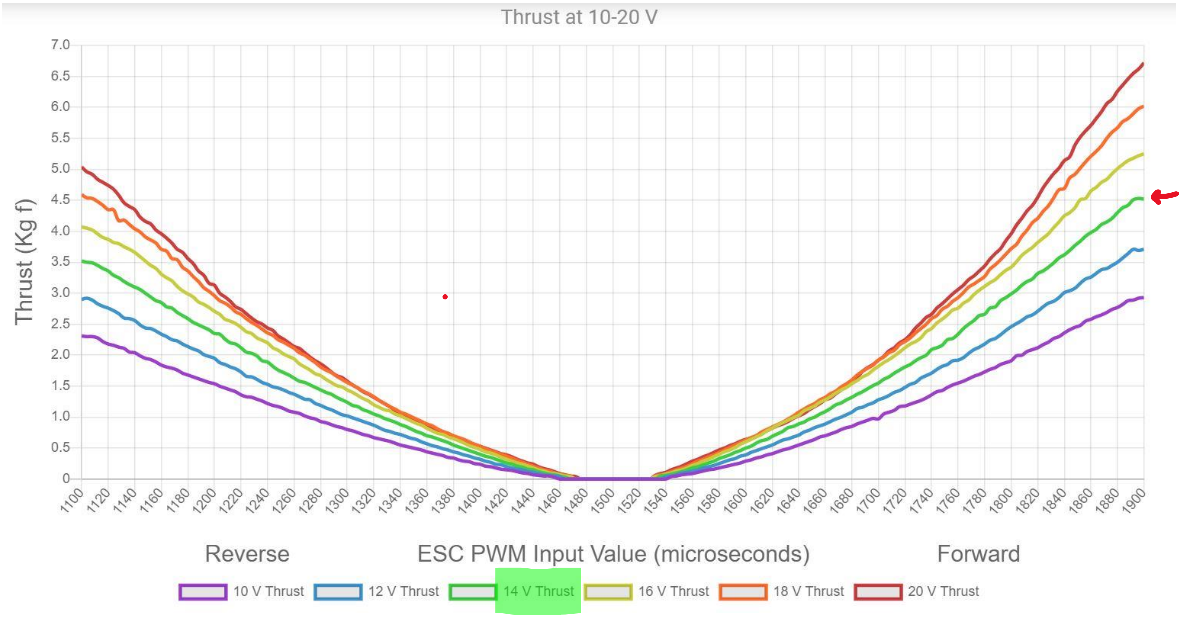

Figure 9: Thrust force vs. ESC input value for supply voltage of 10-20V (Blue Robotics, 2021)

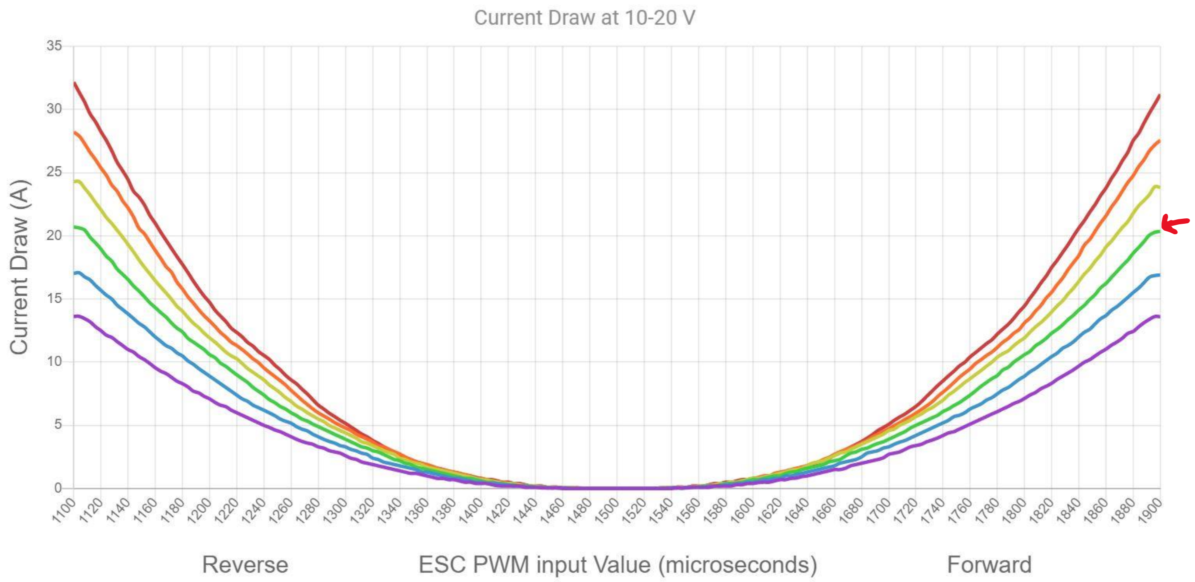

Figure 10: Current drawn vs. ESC input value for supply voltage of 10-20V (Blue Robotics, 2021)

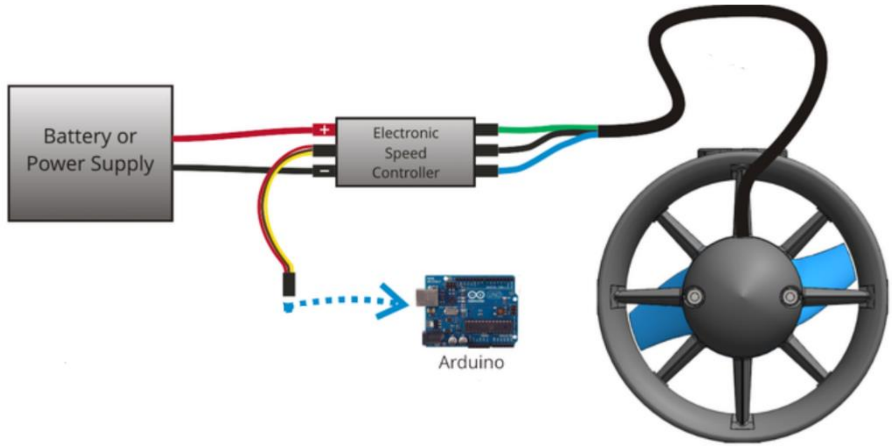

Figure 11: Thruster circuit diagram

5.2 Power Supply

The power supply is designed to be supplied by a nominal 14V battery source. It is further designed and implemented to deliver both a 12V and 5V regulated power supply. The voltage from the power supply fluctuates with time as a result of numerous factors such as heat transfer driven by a temperature difference and the chemical reactions inside the battery. As the battery operates it begins to lose energy, resulting in a voltage drop. There are three DC voltage lines: a 14V, 12V and a 5V line. The 14V is used to supply power to the three thrusters via the electronic speed controllers. The 12V line powers the Arduino Uno, the two submersible pumps and the solenoid water valve. The 5V line supplies power to the relays and the IMU BNO055.

5.2.1 Battery Pack

The battery pack used is a 14V battery pack which can draw up a high drain current of 30A. Each battery is rated at 3.7V but can supply a maximum of 4.2V. Each battery can produce 2500mAh and has a max drain current of 30A. Therefore, if all thrusters are powered at full speed indefinitely, the battery only lasts 27 minutes. This calculation can be confirmed with the equation below.

$$Battery\ Life = \frac{Total\ mAh\ Produced}{Total\ Current\ Drawn} \tag{1}$$

5.2.2 LM2596 Adjustable DC/DC Buck Module

This device is an adjustable voltage regulator step down power supply module with a display. The voltage regulator steps down the 14V provided to the power supply to constant 12V DC to power particular components such as the pumps and relays. Figure 12 illustrates the LM2596 components circuit diagram.

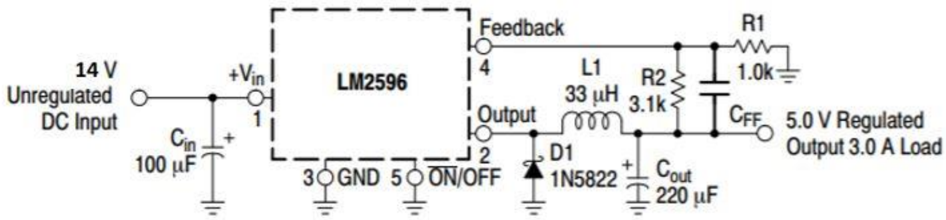

Figure 12: LM2596 adjustable DC/DC buck module circuit diagram

5.2.3 Arduino Voltage Output

The Arduino is powered by the 12V line supplied by the LM2596 DC/DC buck module. Once the Arduino is powered, the 5V output pin on the microcontroller is used to create the 5V line. This supplies power to the relays' low power primary circuit and the BNO055. The 5V output pin connects directly to a five-piece equipment business terminal electrical switches cable building connector to create a 5V bus.

5.3 Relays

Relays are commonly used as an electronic switch. Traditionally, relays are controlled by electromagnets, however newer models use solid-state relays. This device uses a low power signal to drive a circuit, in this project the relays control the solenoid valve and the two submersible pumps. The device provides complete electrical isolation between the controlling and the controlled circuit. The primary circuit integrates the control signal to operate the relay, the primary circuit is powered by the 5V line. The secondary circuit is connected to the load which is being controlled and is powered via the 14V battery. The relays receive signals via the Arduino to turn on/off the pumps when necessary.

5.4 Submersible Pumps

The submersible pumps are used for the ballast tank and is powered using the 12V line. Both submersible pumps are normally closed connected to individual relays with a signal wire connecting from the relay to the Arduino. The signal wire decides (based on the code) when to switch the pumps on and off. Before the pumps begin to operate the solenoid water valve has to be open.

5.5 IMU BNO055

Figure 13 demonstrates how just the accelerometer is connected to the Arduino UNO and how the UNO is powered using the 12V DC power line. The IMU is powered via the 5V pin on the Arduino. The two lines needed for communication for I2C; a SCL (Serial Clock) line and an SDA (Serial Data) line are connected to the allocated analog pins (A4 and A5) on the Arduino. Although not used, the INT pin on the BNO055 could be connected to a digital pin on the Arduino, to trigger interrupts when necessary. This device is used to control the AUVs yaw angle and is integrated into the Y position control system .

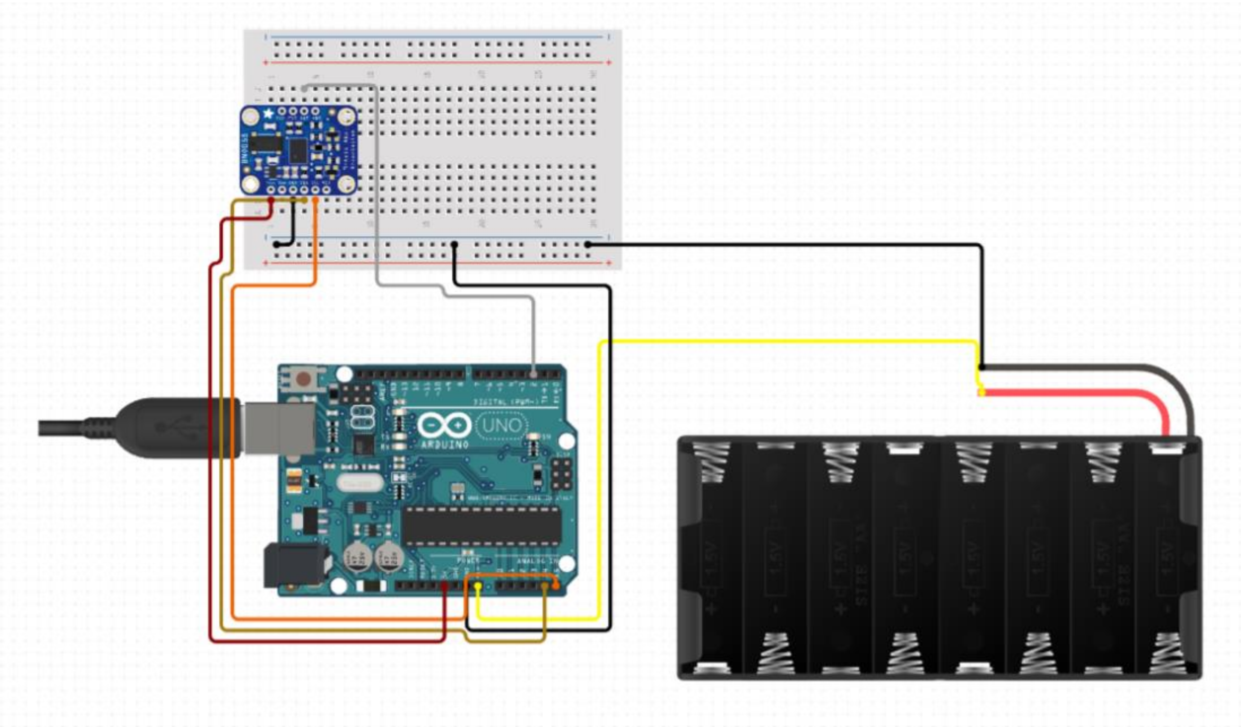

Figure 13: IMU BNO055 circuit diagram

5.6 Solenoid Water Valve

The solenoid valve is connected to the load side of the relay and 12V line. While the primary end of the valve's relay is powered by the 5V line. The solenoid valve opens and closes by sending a high/low to the corresponding Arduino digital pin. A delay of at least 4-5 seconds is required for the valve to completely open/close. The solenoid valve is also linked to the pump in via a hose (plastic tube). The circuit diagram for the solenoid water valve can be seen in figure 14.

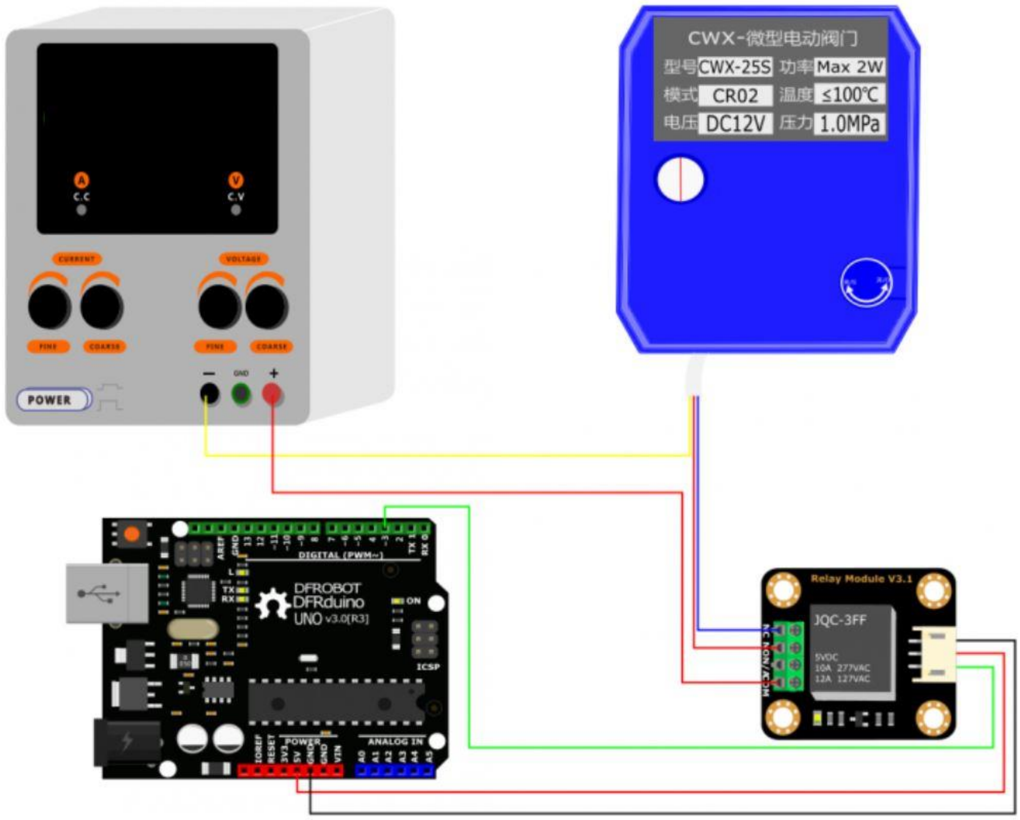

Figure 14: Solenoid water valve circuit

6 AUV Control System Design

6.1 AUV Plant (Kinematic Model)

6.1.1 The Control System Overview

A typical layout for most control systems is given in figure 15 below. The objective is to get the plant's output to match the desired reference at the input.

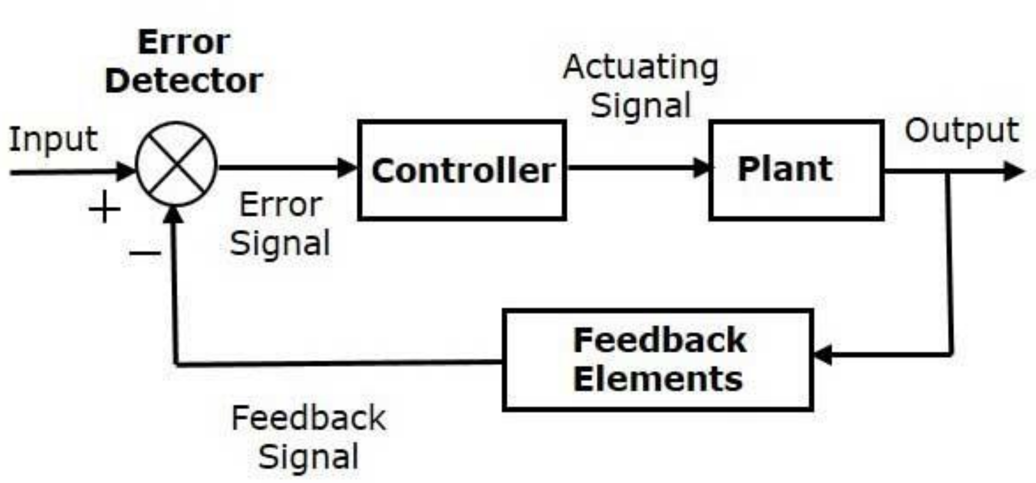

Figure 15: Closed loop control system block diagram

The design of the AUV control algorithms is no different from the implementing the above typical closed loop system. In this case, the Plant = AUV and the Controller creates the actuating signals to feed into the plant and ensures that each time the plant's output is fed back, the error between the reference input and the plant's output is reduced to zero.

The challenge in designing the control system is first to understand what exactly the content of the plant block is (Pshikhopov, 2013). Much time was spent researching different AUV designs, and control systems and it resulted in the conclusion that there is no simple solution or readily available controllers that can be "copied" and plugged into either the plant or controller blocks.

Each AUV design has its own characteristics that depends on thruster locations, orientation of thrusters, shape of body frame, etc (Sharma & Subudhi, 2019). The conclusion from this research meant that this project's AUV PLANT block needed to be modelled as per this project's design chosen thruster layout. The process to describe this project's specific AUV PLANT is called developing the kinematic model whereby the precise control inputs needed to produce a desired output are required to be identified.

6.1.2 Modelling the AUV Plant

The mechanical layout of the AUV is such that it has three thrusters positioned along the mid-point of the structure. figure 16 below shows the mechanical design layout of the thrusters taken during the actual build process.

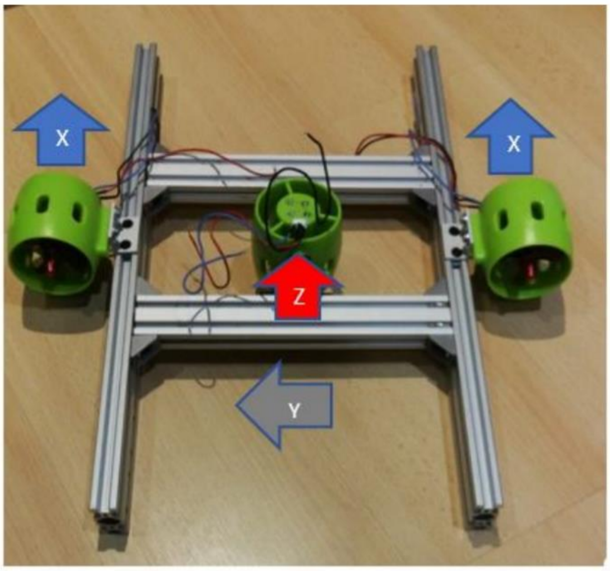

Figure 16: Initial Build of AUV

Since the AUV only has thrusters that would move in X and Z directions, a movement towards a Y coordinate would have to be achieved by generating a moment about the Z-axis, to turn the AUV left or right by varying power to the forward thrusters. Figure 17 below takes a 2D view about X-Y plane to analyse the math involved in calculating the forces and moments needed to steer the AUV.

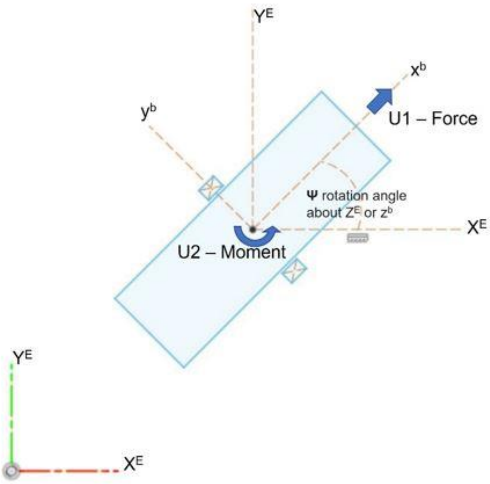

Figure 17: AUV 2-D X-Y Plane view (Top View)

The nomenclature for the diagram in figure 17 is:

U1 = Force (N) in the body frame $X^{\mathbf{B}}$ direction.

U2 = Moment (Nm) rotation about Z^B axis.

Ψ = Psi, the angle of rotation in radians about Z^B.

From the design assumption that the AUV cannot control its pitch or roll degrees of freedom (due to lack of thrusters), and that the AUV operates mostly in calm waters and assisted by horizontal stabilising fins (can be seen in appendix C and F), an approximation can be made that Z^B and Z^E remain parallel to each other. This means that angle of rotation about Z is the same for both the AUV Body frame and the inertial Earth frame.

Thus, the maths to describe the motion of the AUV along the X-Y plane is given by trigonometric equations and Newtons 2nd Law of Motion (Force = mass x acceleration):

$$U_1 = ma \tag{2}$$

$$\ddot{X}_E = \frac{U_1}{m}\cos(\Psi) \tag{3}$$

$$\ddot{Y}_E = \frac{U_1}{m}\sin(\Psi) \tag{4}$$

Equation (3) and (4) refer to the acceleration in earth frame for the X-direction and the acceleration in earth frame for the Y-direction.

$$U_2 = M_Z = I_{ZZ}\ddot{\Psi} \tag{5}$$

Equation (5) shows U_2 (moment about Z) = mass moment of inertia about Z x angular acceleration. Therefore:

$$\ddot{\Psi} = \frac{U_2}{I_{ZZ}}$$

(6)

Equation (6) shows the angular acceleration about Z.

The acceleration in X-Y plane is noted by non-linear equations (has cosine and sine functions) and hence a linearisation needs to be performed for the control system. To do this consider the current and next states or current and previous states.

At a steady state (when AUV is at rest and about to move), the ψ angle very small or zero and hence cos ψ = 1, and sin ψ = ψ . Therefore, at steady state:

$$\ddot{X^E} = \frac{U_1}{m}$$

(7)

For:

$$cos\ (\Psi) = 1$$

$$\ddot{Y^E} = \frac{U_1}{m}\Psi$$

(8)

Avoid using sin(0) = 0 but use sin (very small Ψ) = Ψ.

For depth control along Z axis, using Newton's 2nd law equation and assign U3 as the "depth force" control input for the AUV plant. The effect of gravity is offset by the "neutral buoyancy" design assumption and hence is not taken into account here:

$$U_3 = ma$$

(9)

Therefore, the depth acceleration is given by:

$$\ddot{Z^E} = \frac{U_3}{m}$$

(10)

Equation (10) is used to calculate the acceleration in earth frame Z-direction.

The linearised AUV PLANT can therefore be represented using equations (6, 7, 8 and 10) follows:

$$\ddot{X^E} = \frac{U_1}{m}$$

$$\ddot{Y^E} = \frac{U_1}{m}\Psi$$

$$\ddot{\Psi} = \frac{U_2}{I_{ZZ}}$$

$$\ddot{Z^E} = \frac{U_3}{m}$$

The inputs to the plant are U_1, U_2, U_3. The outputs XYZ and psi can then be derived by double integration of the respective acceleration vectors.

The open loop block diagram representation of the AUV plant designed in MATLAB Simulink is shown in figure 18.

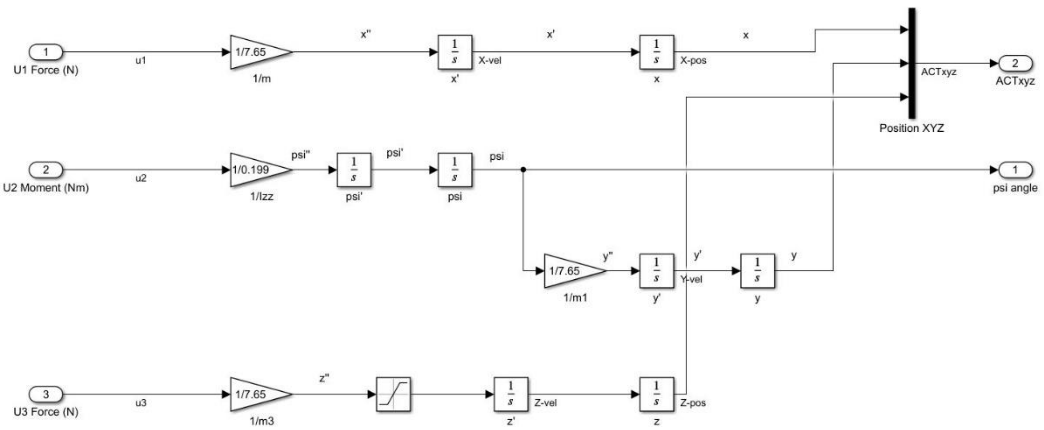

Figure 18: AUV Plant model in Simulink

6.2 Modelling the AUV Controller

The controller accepts position reference inputs (XYZ_{ref}) in the earth frame and then translates these into force and moment vectors (U_1,U_2 and U_3) to be fed into the AUV Plant. The ψ angle is computed from U_2, within the AUV Plant and fed back to the controller as an internal control variable with its own internally generated psi ref. So essentially psi is the “heading” for the AUV and the controller needs to adjust the heading so that a direction towards Y_{ref} is computed. A set of PID controllers shown in figure 19 are used to manage the position error conditions by comparing the actual positions fed back from the plant to the reference inputs.

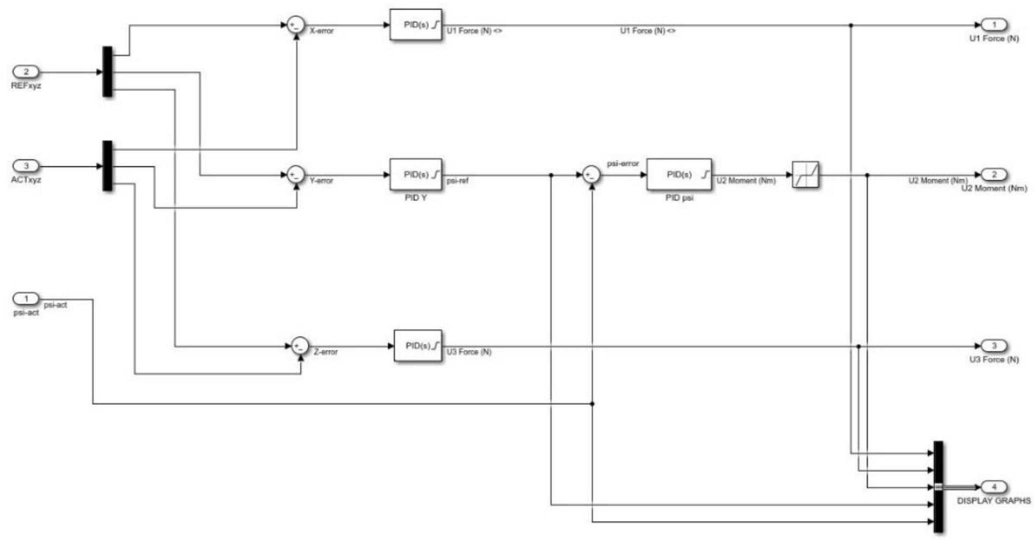

Figure 19: PID controllers’ setup in cascaded format for Y and **ψ** signals

Because the Y_{act} position is derived from the changing psi angle as the AUV navigates to its target position, two PID controllers for U_2 (Moment about Z) are needed and are thus configured as cascaded PIDs, with the inner-loop computing psi act and the outer-loop then computing Y_{act}. For this reason, the overall behaviour of the PID controllers result in the Yref target being reached last, after Xref and Zref. The X and Z PID controllers are simply used to generate U1 (Force X) and U3 (Force Z). It is important to note that “positive Z” is set to point upwards, meaning that to dive to 5m then the Z_{ref} is set to - 5m.

6.3 Initial Results of the Control System

The control system design this far is shown in figure 20. The reference signals are specified in the inertial Earth frame XYZ_{ref} and the PID controller generates the actuating signals U_1,U_2 and U_3 into the plant which then feeds back [XYZ]act and Ψ_{act}. The PID controllers were tuned, using the auto tuning function built into Simulink. A display module was created to depict the results of the simulation. An initial test of the XYZ_{ref} = [5 -5 -5] yielded the following results in 3-D shown in figure 21.

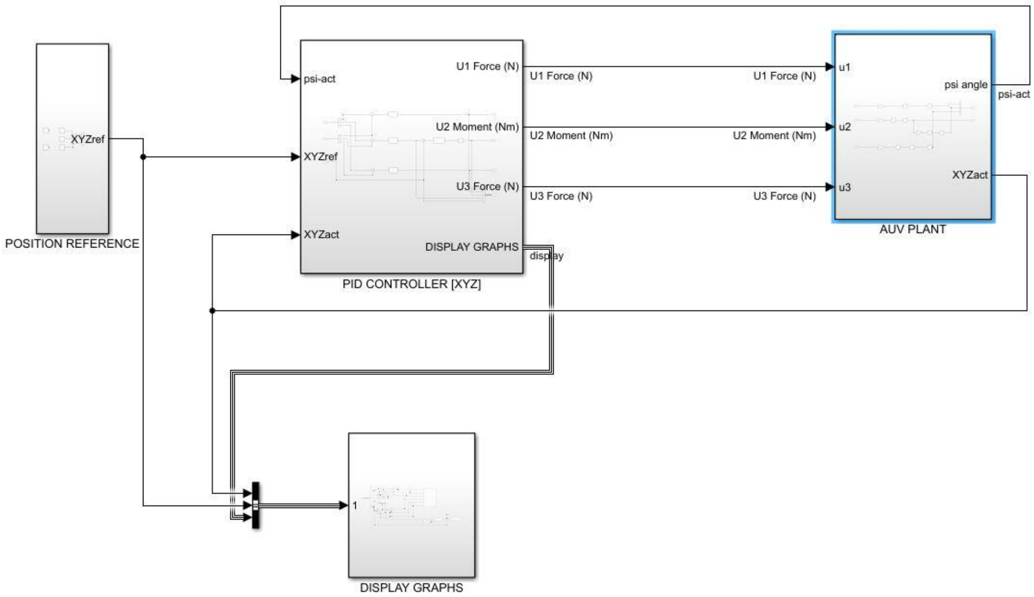

Figure 20: AUV control system model (without environmental considerations)

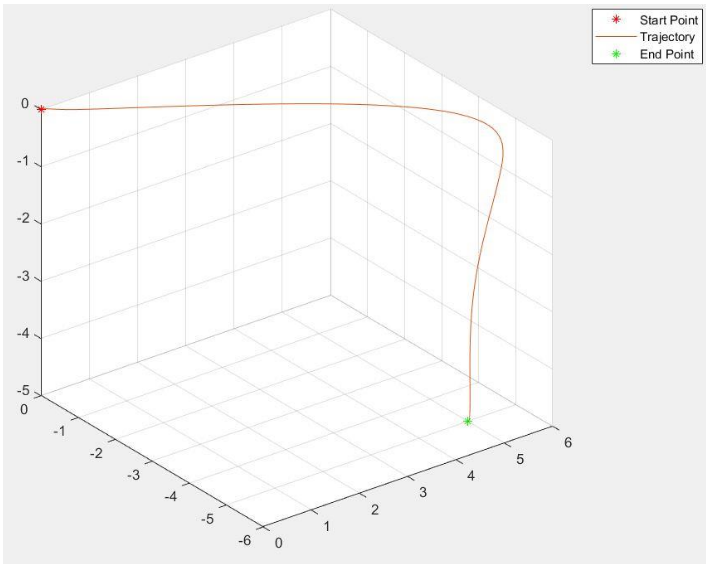

Figure 21: Results without constraints

The AUV moved to its specified reference position [5 -5 -5]. However, a closer analysis of the results yielded that more work on the model was required. The AUV appeared to move towards XY_{REF} very fast (less than 5 seconds) and the forces and moments were extremely high. It was clear the mathematical model was calculating the forces and moments to move the AUV in a "vacuum" with unlimited power available to the thrusters.

The model was updated to include limitations on the thrusters. The specification sheet of the Blue Robotics thrusters at 14V DC indicates a maximum thrust of 4.5 kgF (kilograms force). This is equivalent to approximately 45 N. The two X thrusters' force were limited to +/-90N forward/reverse in a saturation block and the Z thruster is limited to +/- 45N. It was also noticed that the AUV made multiple 360^{O} turns during its motion. A saturation of +/- $\frac{\pi}{2}$ was added in for the $\boldsymbol{\Psi}$ angle part of the controller. This meant that the AUV is limited to the design capacity of the thrusters and the "heading" are limited to turn either full left ($\frac{\pi}{2}$ radians) or full right (-$\frac{\pi}{2}$ radians) from its start-up position set as X^B=X^E= 0 (where X^B and X^E point in the same direction).

These additions to the model corrected the AUV's motion to more realistic results. However, the important aspect of underwater travel and the impact of hydrostatic and hydrodynamic forces and moments still needs to be considered and the next section describes in greater detail.

6.4 AUV Underwater Environment

Modelling the AUV underwater was left to a very late stage in the design since the final specifications of the AUV with regards its dimensions, weight, and centre of gravity were needed to make the final calculations about its buoyancy. It is therefore important to note that should the AUV be upgraded as a future study project, this part of the Simulink model needs to be adjusted accordingly. For example, if one adds a sonar device its mass and volume displacement will change the buoyancy of the AUV. Calculation for the volume of the AUV is attached to appendix D (D.1).

6.4.1 Hydrostatic Forces on the AUV

The AUV underwater experiences a force that pulls it down due to gravity, and also a force that pushes upwards due to the pressure of water that the AUV displaces. The formulae relating to the two forces are:

$$F_{HS} = F_{BUOYANCY} - F_{WEIGHT} = \rho g V - mg \tag{11}$$

Where:

ρ = density of sea water (1023.6 kg/m^3)

g = gravity at 9.81 m/s^2

m = mass of AUV

V = volume of water the AUV displaces

To get to a neutrally buoyant AUV, which stays submerged at a specific depth requires F_{HS} = 0 and hence its mass should be:

$$m = \rho V = (1023.6)(0.0075) = 7.677\ kg$$

The volume of the AUV was determined to be 0.0075 m^3. The calculation for this is found in appendix D (D.1) and involved calculating the volume of each structural component of the AUV. For the purposes of this model, the mass needed for neutral buoyancy was kept constant. The force of water buoyancy does change as depth changes and should be considered for the next phase of the AUV development.

6.4.2 Hydrodynamic Forces on the AUV

The AUV is also subjected to hydrodynamic forces with respect to water resistance (drag and lift). Only the drag force is considered for this project and an approximation was made the lift force is zero because the AUV travels very slowly. Other forces not considered are the water currents and sway motion of the AUV.

The drag force impacts the AUVs motion such that as its forward velocity increases, the drag increases (Stevenson, 2009). At rest, the AUV drag force = ZERO.

The formula for computing drag is :

$$F_{DRAG} = \frac{1}{2}\rho v^2 C_d F A \tag{12}$$

Where:

ρ = density of sea water (1023.6 kg/m^3)

v = velocity of the AUV in the direction of travel [XYZ-vel]

Cd = coefficient of drag = 0.85 for the typical shape of this project's AUV (Aziz, 2008)

FA = frontal area of the AUV (FA_X 0.25 x 0.15; FA_Y = 0.50 x 0.15; FA_Z = 0.50 x 0.25)

The calculations for Frontal Areas of the X Y & Z planes of the AUV were just approximated to be its respective box shapes for the purpose of this initial stage of modelling. A more accurate estimate requires taking each component of the AUV and calculating the area with respect to its 3D plane. F_{DRAG} is a function of velocity squared and the control system design would need to feed back a velocity vector from the AUV Plant model to calculate the varying impact of drag on the motion of the AUV.

6.5 Updating the Control System for the Environment

Figure 22 is the completed AUV model that includes the impact of the environmental hydrostatic and hydrodynamic forces. It now feeds back the velocity vectors XYZ-vel from the AUV PLANT to the ENVIRONMENT module of the control system.

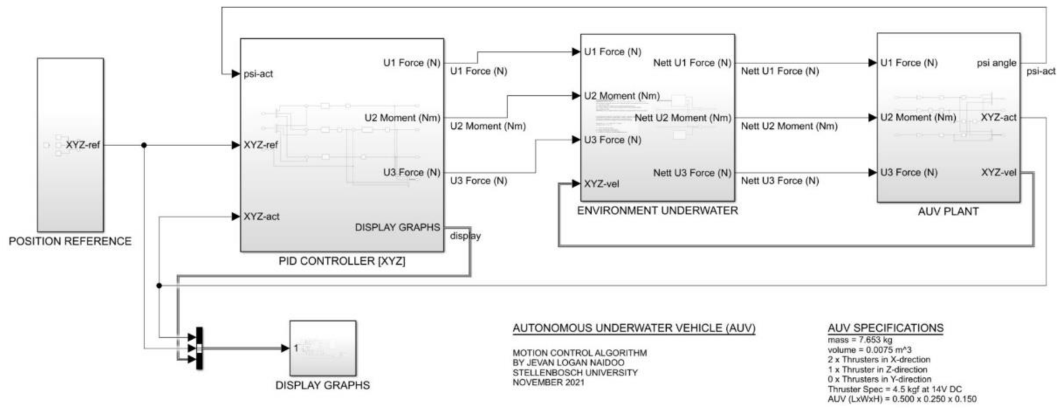

Figure 22: AUV Control System with Environment (Top Level)

The model from the previous section has now been updated to include the impact of environmental forces and moments on the AUV. The AUV Plant also now outputs the velocity vector into the environmental block so that F_{DRAG} can be dynamically calculated as the AUV adjusts its speed as it moves towards its reference target. Appendix D.3 contain the complete Simulink model used in this section.

The results for a simulated run of the model now with environmental hydrostatic and hydrodynamic forces and moments now included in figure 23 for the same

XYZ_{REF} = [5 -5 -5] but now yields a slightly different trajectory than the one without drag and buoyancy taken in account.

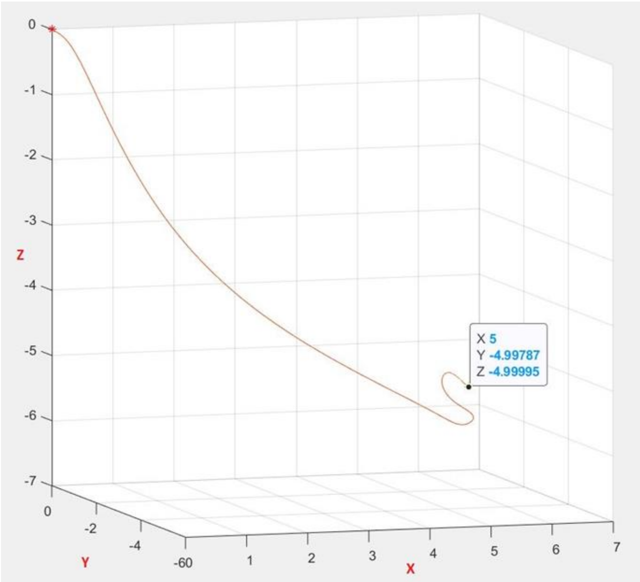

Figure 23: Trajectory of the AUV with drag and buoyancy included

The PID controllers produce the required thruster forces and moments to guide the AUV to its target, however with the opposing forces, especially drag, the AUV overshoots its target along X and Z by about a metre, shown in figure 24 below, and then corrects itself whilst steering towards Y. It is expected that with more time spent on improved tuning of the PID controllers, the level of overshoot can be minimised further.

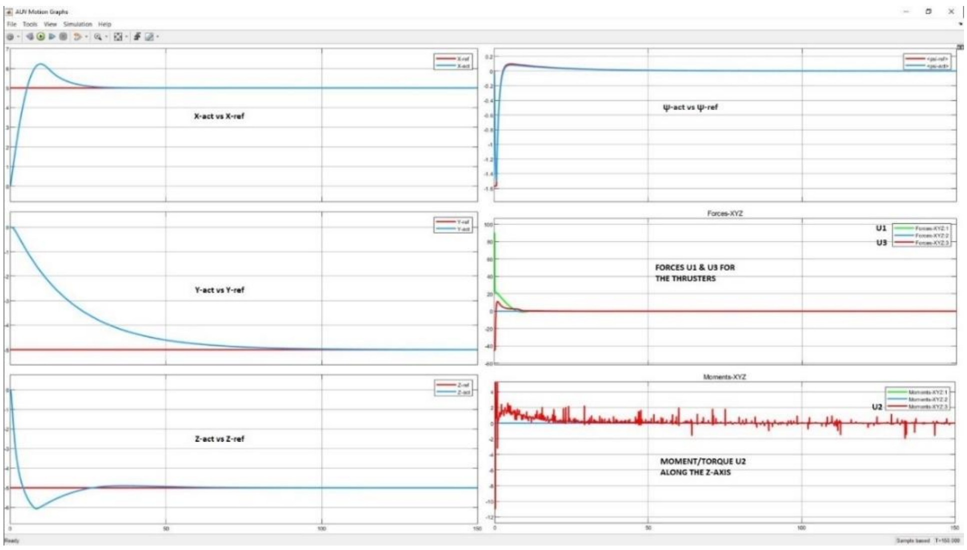

Figure 24: Motion control graphs of the AUV and environmental conditions

7 AUV Ballast System Design

7.1 Background

The project brief required the design of an appropriate ballast system that would keep the AUV at a constant depth when all its thrusters are turned off.

This is an important functionality to have because if the AUV is not designed to be neutrally buoyant then it will either float or sink when all thrusters switch off. In this situation, the depth thruster (Z) needs to be constantly working to maintain a particular depth and consume unnecessary energy of the on-board battery pack.

The ballast system is thus meant to stabilise the AUV to a particular depth and its design should be such that it consumes less battery power than the depth thruster.

7.2 Types of Ballast Systems Considered

There are various types of ballast systems for underwater ROVs and AUVs, but the overall concept is similar, namely, to change the weight of the AUV by controlling how much water is contained in a special tank, called the ballast tank (Tiwari & Sharma, 2020). For this project, the following types of systems were considered (seen in figure 25) based on simplicity to build and its cost.

- piston driven mechanism
- pumps driven system

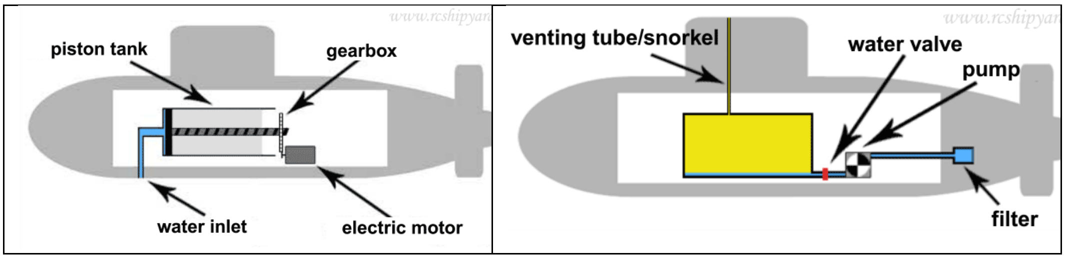

Figure 25: Piston and Pump type Ballast System

The piston type system is easier to control the precise amount of water taken into the ballast tank by using encoders to read the motor rotation and depth of the piston. However, waterproofing the electric motor/shaft from the ballast tank is complicated. Even the simplest solutions of using a medical syringe and a motor to drive the shaft can become tricky to assemble in practice.

The water pump system is easier to implement because it does not require a system that's completely waterproof. Cheap submersible DC pumps are easily available in the market. This system is less precise as the piston system because without sensors to measure the volume of water in the ballast tank, one would need to rely on the volume flow rates of the pump.

The challenge however for this project is how to handle the air displacement created by an in-take of water into the ballast tank. Venting air into the ocean was not an option as this meant that the AUV would need to surface to refill its ballast with air – without air to push out water from a filled ballast tank, the only way to surface would be to start up the depth (Z) thruster. If this thruster malfunctions, then the AUV could remain lost underwater.

Moving air into the electronics compartment was initially considered but the risk of water flooding the electronics section was too great, unless each section is properly water sealed.

The biggest obstacle building the AUV was preventing water leaks. With limited resources available to the project, it was decided to separate the ballast tank module from the electronics module and the only connection between the two would be for power to the ballast tank. This decision led to the choice of the pump-type ballast system design instead of the piston driven system. So only thin power wires are fed to the ballast system from the electronics compartment and nothing else. If it were easier to seal the electronics compartment housing a stepper motor and threaded rod to drive the ballast piston then the piston type setup would probably been selected.

7.3 The Design of the AUV Ballast

7.3.1 Sizing the Ballast Tank

The tank size in the case of this project's AUV's functionality does not need to be designed to any specification. This is because the design approach assumption is to make the AUV as neutrally buoyant as possible. This means that the AUV can maintain at a submerged depth that it is taken to by the depth thruster (Z). For the design of the AUV, including the ballast tank (half filled) the neutral buoyancy mass = 7.653 kg.

Off course, it is not practical to get to exactly 7.653kg mass and the ballast tank is thus intended to trim the weight of the AUV to neutralise the effect of any residual buoyancy. The size of the ballast tank for only this trimming function is thus not a serious design constraint. Noting that mass of 100g = 100ml of water, an acrylic cylinder of 80mm inner diameter and 150mm height which yielded an approximate volume of 750ml was used for the tank.

The ballast tank thus has the following specifications:

Volume = 750 ml

Weight (water) = 750g

With the tank being half filled at initial launch, the ballast can regulate the weight of the AUV by +/- 375 grams. This is considered sufficient to meet the requirement that the ballast tanks only serve the purpose of keeping the AUV at a steady depth when all the thrusters are switched off.

Fully de-ballasting the AUV, even with all thrusters switch off, results in the AUV surfacing as its neutral buoyancy setup leads to being biased to a positive upward buoyant force. This is a good safety feature and can be used to surface the AUV as the battery runs flat.

7.3.2 The Ballast Tank Module Design

Figure 26 shows the final ballast tank assembled on the AUV structure and gives the reader a view about what the prototype setup looks like. Each component is explained further and why it was necessary to include as part of this design.

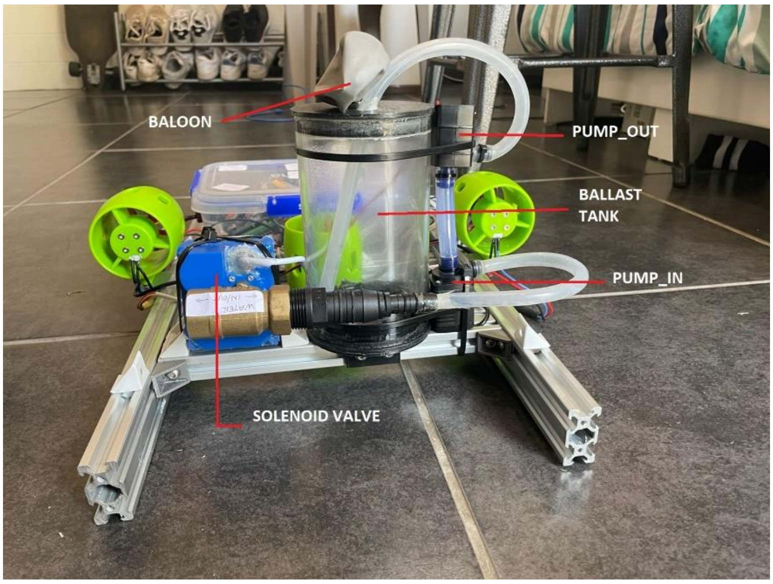

Figure 26: Assembled Ballast Tank Components

The ballast system comprises of a tank, two mini 12V DC pumps, a solenoid valve, and a balloon fixed at the top of the tank.

Two water pumps are needed because it was not possible to buy a single reversible pump. The pumps are connected in series and only one pump should be operated at a time. After much experimenting with various assembly options, it was found that when underwater, and water is pumped into the tank, the existing air in the tank needed to be vented somewhere other than just being compressed in the ballast tank or sent into the electronics case. For this reason, a balloon was chosen as it provides the elasticity needed to compress air which is needed to assist pumping water out of the ballast tank. The solenoid valve is critical as it is used to close the water inlet/outlet and prevent water from leaving the tank after the pumps are switched off and the balloon is filled with compressed air.

Options of leaving the compressed air in just a partially filled ballast tank was explored but this seemed to cause too much pressure build up in the ballast and caused the seals to break and air to escape and be lost. This air is needed to ensure water can be pumped out of the ballast and hence the need for the balloon. The system does work, even though it does not look aesthetically appealing. A future modification maybe to house the balloon in a separate tank and vent out any air from that tank as the balloon first inflates. At least then there is no balloon inflating underwater making the AUV unstable from ocean currents and altering its centre of buoyancy.

7.4 The Ballast Tank Control System

The control system for the ballast tank works independently from the control system for the AUV thrusters. The ballast system is only meant to operate when the AUV has reached its target reference position and all thrusters are switched off. So, when $XYZ_{act} = XYZ_{ref}$ the thrusters can be switched off and the ballast can maintain the depth.

For the ballast control system to work it requires a depth position reading from an on-board depth sensor (not yet installed on the AUV due to high cost). The sensor reads water pressure, and this is converted to a depth measurement in meters. The control system then uses the Z_{ref} position as a reference input and compares it to the depth reading from the depth sensor for any changes thereafter. A PID controller is then used to regulate how much of water is fed in/out the ballast tank to change the weight of the AUV to keep it at a depth close to Z_{ref}. Figure 27 shows a block diagram in MATLAB/Simulink for the design of the ballast tank control system. This was not fully tested on the AUV because the depth sensor was not purchased/installed.

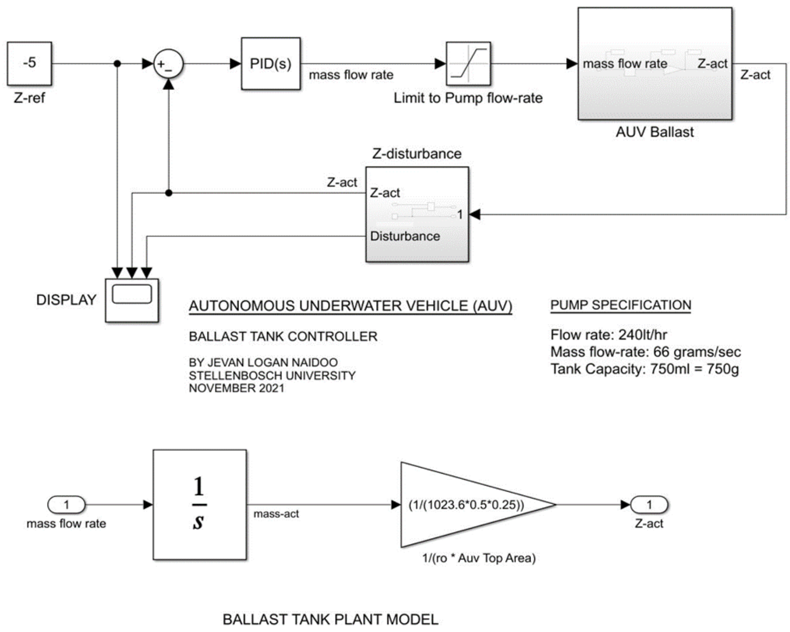

Figure 27: Ballast tank controller

The actuating control input was identified to be the mass flow rate of the pumps and the output signal to be controlled is the Z-act position (depth) of the AUV. The setup is such that Z-ref (-5m) is the depth level of the AUV when all thrusters are switched off. The controller must therefore regulate the mass flow rate of water pumped into or out of the ballast tank to change its weight and then keep the AUV at the Z-ref depth. To verify the controller does work a disturbance is fed into the system. The output Z-act must therefore respond by moving back to -5m depth. This is shown in the results graph in figure 28.

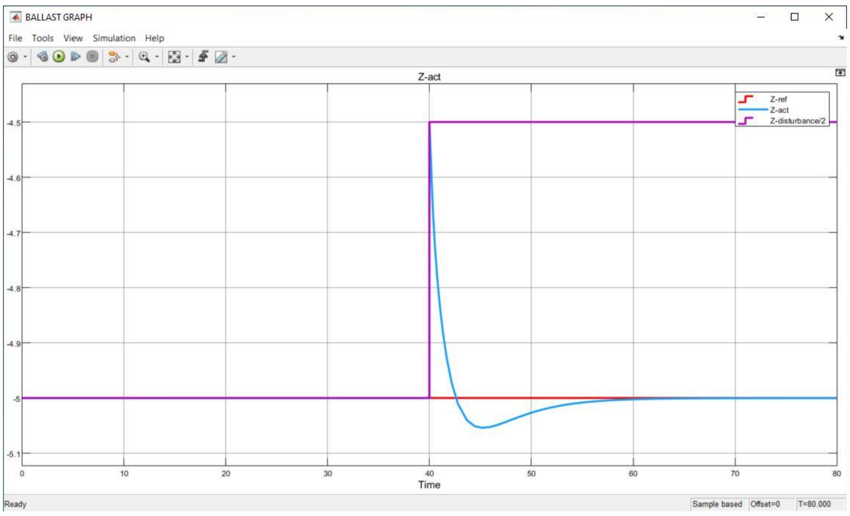

Figure 28: Ballast tank controller returns AUV to reference depth (-5m)

The AUV is parked at -5m depth, at t=40s a disturbance is encountered and moves the AUV up to -4.5m. It takes the controller about 20 seconds to adjust the mass of water in the ballast tank to return the AUV to -5m depth.

The mathematical model for this is explained below:

At rest

$$F_{BOUYANCY} = F_{WEIGHT}$$

(13)

the AUV is designed to be neutrally buoyant at 7.65kg

Equation (13) can be rewritten as:

$$\rho g V = mg$$

(14)

where ρ= density; V = volume displacement and m = mass

Since Volume = height . area therefore:

$$\rho g h A = mg$$

(15)

this reduces to

$$h = \frac{m}{\rho A}$$

(16)

or

$$m = h\rho A$$

(17)

The AUV can be taken as a flat rectangular plate floating underwater with the buoyance force upwards = the downward weight force. Thus, the height (depth) at which the AUV is floating is given by its mass divided by the water density x Area of the rectangular plate.

The rate of change of AUV mass (ṁ) is effectively the pumps pushing water into/out of the AUV ballast tank. With some calculus it can be determined that:

$$\dot{m} = \frac{dm}{dt} \tag{18}$$

$$\frac{dm}{dt} = \frac{d(h\rho A)}{dt} \tag{19}$$

$$\frac{d(h\rho A)}{dt} = \frac{dh}{dt}\rho A + \frac{d(\rho A)}{dt}h \tag{20}$$

$\dot{m} = \frac{dh}{dt}\rho A$ since density and area are constants. Therefore, the height (depth of AUV) can be controlled by means of the pumps mass flow rate and this is how MATLAB/Simulink is configured in figure 27. Appendix D.3 contains the complete Simulink model designed in this section.

8 AUV Code and Algorithm Logic

8.1 Arduino Code Flowchart

The source code for the AUV is a translation of the control systems logic from MATLAB/Simulink into a C program that works on the Arduino Uno. Figure 29 below depicts the source code in a flow chart format.

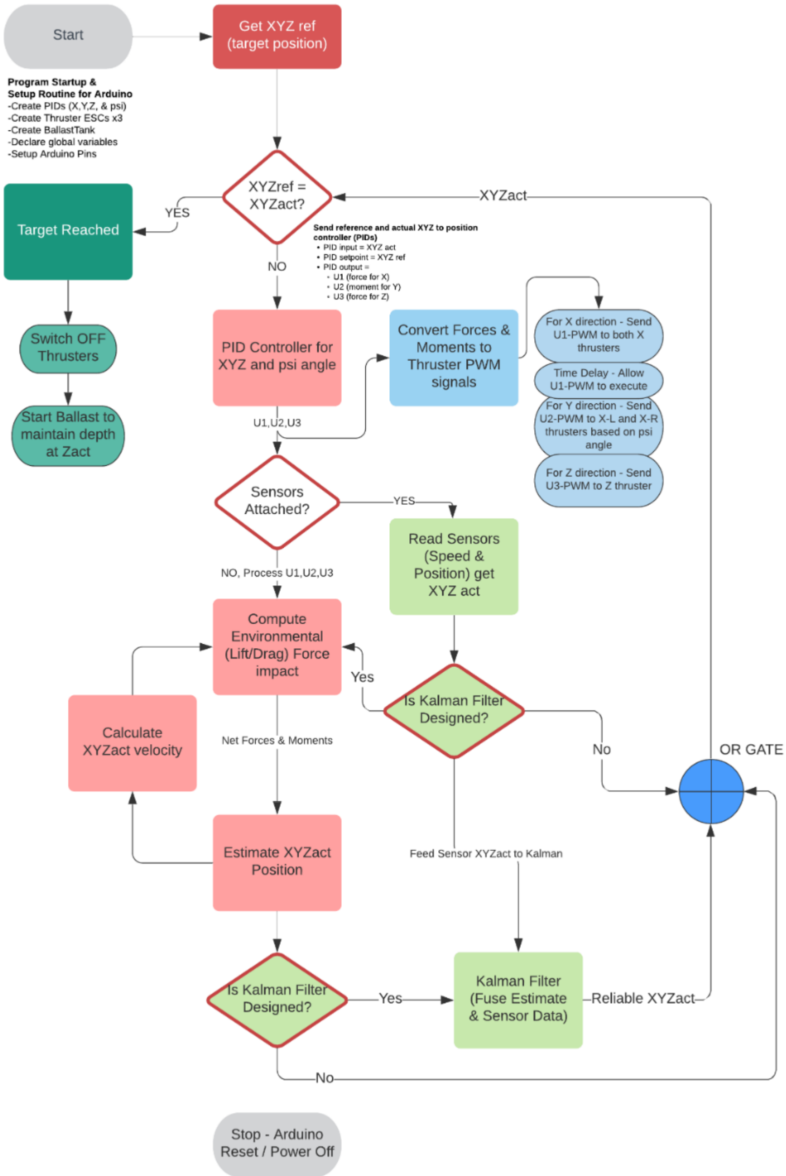

Figure 29: Arduino Source Code Flowchart

8.2 Program Functionality with/without Sensors

The source code is available in appendix D (D.2.1 and D.2.2) and this section only describes the program logic implemented to achieve the objectives of moving the AUV to a predefined reference position and to turn on the ballast system when the AUV reaches the target.

The code is designed to work without expensive sensors that track precise velocity and distances travelled. This is achieved using position estimation instead of reading actual sensor information. In a second phase of the project, sensors such as underwater GPS, pressure sensors, sonar, etc. can be added and fed directly into the calculations.

The challenge of developing the source code to work with position estimation techniques is that the position estimates need to also account for the effects of underwater drag forces acting on the AUV. If the AUV is fully equipped with on-board motion sensors that can track its position in 3D space, then there is no need to account for internally computing the effect of hydrostatic and hydrodynamic forces and the source code can be largely implied.

The flowchart in figure 29 shows the process of building the source code to operate with and without sensors, and the blocks in “light green” should be implemented as sensors are attached. The flowchart also indicates the added benefit of using a Kalman Filter to combine position estimates with actual sensor information. Depending on the quality of commercially available sensors, even information obtained from them is not entirely accurate due to “drift” and external forces underwater. The Kalman Filter is hence used to fuse sensor information with position estimation information to obtain a more reliable / accurate position of the AUV as it moves underwater.

8.3 Position Estimation (without sensors)

The position estimation algorithm in the source code uses the outputs of the PID controllers for XYZ to compute the forces and moments needed to create the PWM signals to be sent to the thrusters. The PWM signals are computed using the thruster specifications of the Blue Robotics T200 thrusters. The actual thrusters used in the project are cheap replicas sourced from China and do not have such detailed specifications charts as supplied by Blue Robotics. They however do have the same PWM parameter settings [max reverse:1100; Stop:1500; max forward:1900]. A program function is used to map forces and moments into thruster direction and speed signals, and this is shown in the “light blue” part of the program flow chart figure 29.

The elapsed time between each cycle of the Arduino loop is measured and this serves to internally compute the acceleration and hence position estimates of the AUV's motion. The onboard IMU is used only to calculate the Yaw (psi-angle) rotation of the AUV. It was not possible to use the IMU to read accurate acceleration/velocity due to the inherent drift in such sensors. Instead, the new position is estimated for each program loop cycle, using physics (Newtons 2nd Law) since the forces from the PIDs and elapsed time and the physical mass of the AUV are known. The opposing drag forces acting on the AUV are also estimated by using the algorithms built in the Simulink model designed in Chapter 6 and a net force is used to estimated next position in the AUVs trajectory.

8.4 Results of the AUV testing

Testing the prototype AUV was the most challenging part of this project and at times the most frustrating. What appeared correct and logical "on paper" did not immediately perform correctly in practice.

In addition to this, working underwater, made it extremely difficult due to the water leaks into the electronics enclosure. Whilst this project aimed at lowering the cost to build the prototype model, it is recommended that a more suitable underwater enclosure is procured to make simple future testing. Due to repeated opening and closing of the electronics enclosure, the water proofing seals needed constant attention and caused much unnecessary frustration.

Testing was restricted to resources of a small swimming pool of 5.4m length, 3m width and depth of 1.6m. Deep ocean testing was not conducted due to costs and risk of losing a run-away AUV.

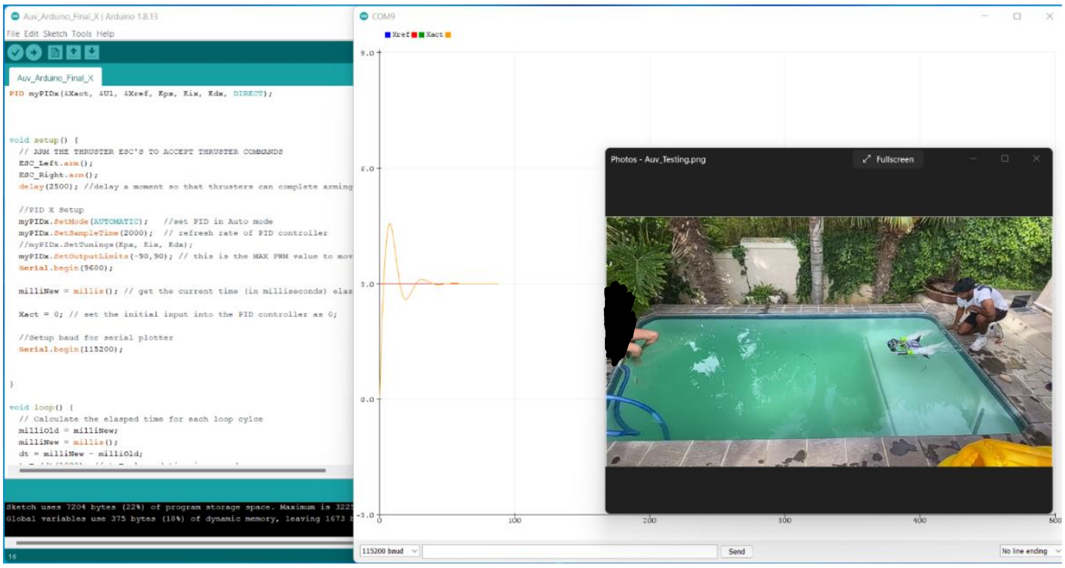

Figure 30: Test 1 results and testing environment

The test plan comprised the following sequence.

A) TEST 1 – PIDS tuning

It took some iterations to tune the PIDs to respond correctly. When tuning a PID system set all gains to zero and start tuning the proportional gain first, then the integral gain and lastly the derivative gain (Bista, 2016). With the swimming pool being only 5.4m in length, the AUV was overshooting the length of the pool for an Xref target of greater than 3m. In figure 30, it was determined that an appropriate PID setting would be Kpx = 0.8, Kix = 0.15, and Kdx = 0.9. This allowed the controller to reach a target Xref = 3.0m. It did this by overshooting to 4.5m and then reversing the thrusters to return to below 3m in a forward/backward motion and settling at 3m. This confirmed that the state estimation algorithms for the Arduino code was working correctly.

B) TEST 2 – Straight line testing

This was the most difficult part of the AUV testing as the Simulink model and the Arduino code for the control algorithm relies entirely on the assumption that the AUV is well balanced with its centre of mass/gravity virtually dead centre of the machine. Since there are no additional thrusters to compensate for any pitch and roll movements, the AUV can veer off in an unintentional trajectory. This happened on many occasions in the initial testing and careful attempts were made to balance the AUV with counterweights which partially solved the issue.

The other issue was that the cheap thrusters used for the prototype appeared to be not producing the same thrust force when operated at maximum speed. This caused the AUV to bank left when it was set to go straight. To correct this problem and get the AUV to move along a straight-line path, a calibration variable needed to be added to the right-side thruster to reduce its speed to match the left-side thruster's maximum speed. The calibration value had to be obtained via "trial-and error" and for the current weight of the AUV. It is important to note that future development AUV may affect weight distribution and hence re-calibration is necessary.

C) TEST 3 – Turning Towards a Y-coordinate

The Arduino code and the Simulink control algorithms differ slightly when it comes to moving in the XY plane. The reason for this is that physically, the two X thrusters are used for forward motion as well as turning. The simulation model sends Forces and Moments to the AUV plant concurrently and the model responds correctly moving the AUV to a desired XYZ position. The major difference is that the Arduino code uses an IMU BNO055 to track the angle Ψ_{act}. For the AUV to reach the target Y position the AUV first rotates to the corresponding Ψ_{ref} and then travel straight line toward it, that is along the hypotenuse (the triangulated XY coordinate).

Figure 31 depicts the results of test 3, showing a slight overshoot which is then successfully removed gradually by the PID controller.

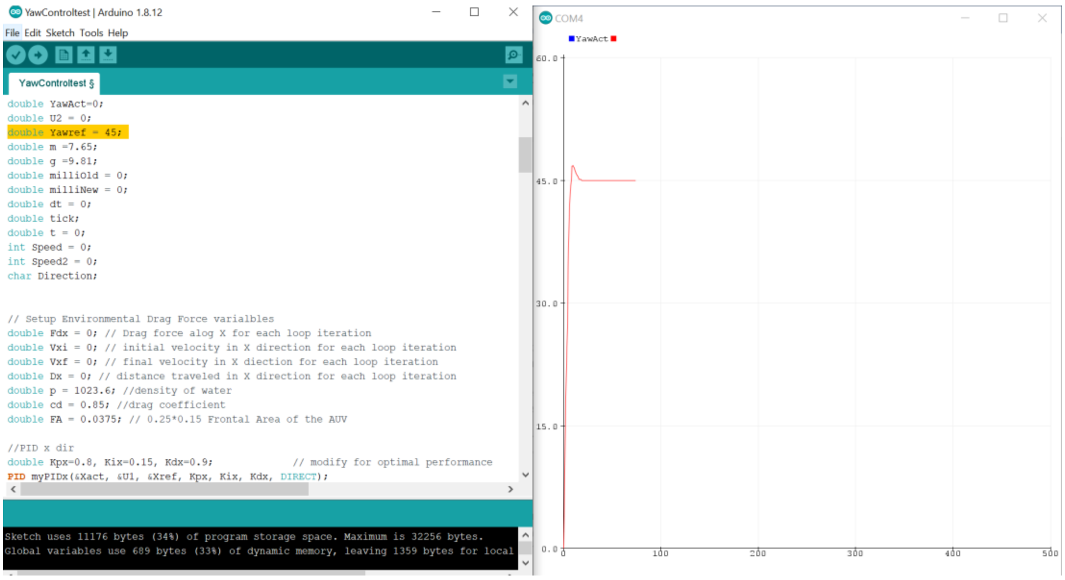

Figure 31: Test 3 results

D) TEST 4 – Depth Testing the Ballast Tank

The ballast tank and its control system are designed to operate when the Zref depth target is reached. The control systems algorithm relies on a reading from a depth pressure sensor. This sensor was not purchased for the prototype due to its high costs. It is a requirement to install the depth pressure sensor to fully test the operation of the ballast tank. The control algorithm needs a reading from the pressure sensor to determine if the AUV has moved away from its target depth. With all thrusters switched off, it is no longer possible to estimate depth using mathematical models. The Arduino code to control the ballast tank is developed but not fully tested. The simulation model on which the code is based has been fully tested in section 7 of this report.

9 Recommendations

9.1 Upgrades and Advancements

Whilst the AUV designed in this project has met the objective of achieving basic autonomous motion underwater, it does have various limitations and the following recommendations are worthy upgrades for future enhancements to the base design.

- A sonar/imaging scanner can be integrated to allow for the AUV to map the terrain underwater and assist in obstacle avoidance (Mangshor, 2019).

- Incorporating an underwater GPS. Instead of using the control algorithm to estimate XYZ position of the AUV's motion, more accurate real-time data can be obtained from the use of an GPS device or a magnetic compass (Mangshor, 2019). The possibilities of underwater trackers/GPS will simplify the control system for the thrusters.

- Additional thrusters for roll and pitch control is recommended. The integration of additional thrusters will allow the AUV to have full control over all 6-DOF enabling it to recover if it capsizes underwater, or even prevent it.

- Waterproof electronics enclosure since the prototype used a cheap air-tight lunchbox to minimise costs. Repeated opening and closing during systems testing and Arduino program changes caused water leaks.

- An upgraded ballast tank can make use of a small air compressor to replace the balloon and will be more aesthetic for a production model.

9.2 Software Modifications

Most robotic systems use the open-source ROS (Robot Operating System) to simplify systems design. ROS currently does not offer a control algorithm for AUV robots but has much pre-built functionality for drones and wheels robots. ROS does offer access to SLAM navigation and robotic arm manipulator controllers (Folkesson and Leonard, 2009). Integrating the thruster control algorithms from this project with ROS can be useful as its not yet readily available in the market.

With the addition of additional thrusters, the control algorithm software can be modified to remove complexity of using the yaw angle (Ψ) to move the AUV along the Y-axis.

10 Conclusion

The main objective of this project was to design the control system for a three-thruster autonomous underwater vehicle with a ballast system and to cost-effectively manufacture the design. Images of the final prototype are attached to appendix F with a components list attached to appendix G. This was achieved by identifying cost effective techniques/processes for designing an autonomous underwater robot with limited resources and budget. The lessons learned in this project (e.g., identifying a definitive scope, time management, budget control and need for solid up-front research) is critical to a successful outcome. Even though the end-product may not be perfect, running the project with a project plan and keeping the target end-dates in mind, the need to produce a working product that meets most of its original objectives is better than not completing at all. The "nice-to-haves" can be scoped into the next phase of the project.

The depth pressure sensor from Blue Robotics was the only component that was required but was not integrated into the AUV due to its high cost and procurement issues. This would have allowed for the AUVs ballast control system to be fully tested. At present the control system is designed to read simulated data from a "virtual depth sensor" and its implementation on Matlab/Simulink proves it will work when the depth sensor is purchased and installed. The AUV is designed to be neutrally buoyant. Its sea water volume displacement requires the mass to be maintained close to 7.65kg. This design saves battery energy, and the thrusters can be switched off when a target depth is reached. The AUV does not immediately surface nor sink. The ballast tank serves only as a trimming device to maintain current depth without the need to operate the thrusters.

The control system design is based on a 3-thruster implementation with two forward pointing thrusters and one depth thruster. The simulated and test results prove that the AUV can move autonomously to a specified target position. Should additional thrusters be added, or the existing thrusters be re-positioned, the control system design and software must be adapted to account for this.

The techno-economic analysis of the project can be found in Appendix E. The project was completed R31 416.80 under budget and on schedule. The typical market retail price of ROVs is close to R30 000 and these are not autonomous robots. Fully automated AUVs are purpose built for specialised underwater applications and are not easily available off-the-shelf. These AUVs exceed R80 000 and hence this project achieved successfully building a low-cost AUV that can be used as a steppingstone for future research and development at Stellenbosch University and beyond.

11 References

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Appendix A Safety Report

A.1 Overview of Testing

The project entails developing an autonomous underwater vehicle. As part of the development, major components of the AUV are tested. Firstly, individual electronic components are tested to mitigate faulty components. The next stage of testing involved ensuring that each component is receiving the correct supply voltage and/or PWM signals. This stage comprises of simple voltmeter tests and oscilloscope measurement readings (for the allocated Arduino pins). These tests were conducted in the Electronic Laboratory where DC power supplies and oscilloscopes are present.

The equipment used:

Equipment:
Multi-meter
DC Power Supply
Oscilloscope

A.2 General Lab Safety

The following general lab safety instructions are applicable:

- No afterhours testing may be performed without the necessary permissions.
- Closed shoes must be worn at all times.
- Loose clothing may not be worn.
- Hair must be tied and out of the way at all times.
- Good housekeeping practices should be kept during testing.
- No food or drink is permitted in the lab.
- Safety report must be visible and accessible during testing.

- All electrical wires and connections must be properly labelled and insulated.
- A safe distance should be kept from system when in working mode.
- Observe emergency exit and fire extinguisher locations.
- Mask must be worn at all times and social distancing must be kept due to the COVID-19 protocols.
- Make sure the power is off and unplugged before changing wiring.
- Keep your hands away from all moving parts of the lab setup.
- Double check your connections.
- Beware of objects with sharp edges.

A.3 Activity Based Risk Assessment

Table A1: Activity based risk assessment of the testing procedure

Activity	**Risk**	**Risk type**	**Mitigating steps**
Entering the lab	Hand Injuries from door	P	Ensure all body parts are out the way of the spring-loaded door.
Turning on equipment	Electrical Shock and components short circuiting.	P/E	Momentarily check over cables and wiring to ensure no short circuits occur (while power is off). Ensure that insulation is thorough.
Moving around lab	Tripping	P/E	Be mindful of your surroundings. Do not trip over cables, wires, or knock into

			the desks. Ensure to be careful when carrying equipment.
Falling objects	Objects/equipment/tools can mistakenly be dropped.	P/E	Wear closed shoes.
Moving equipment/parts	Clothes, hair, or body parts may get caught, stuck, or pulled into the moving components.	P/E	Ensure that all body parts and loose wires are kept away moving equipment. Ensure loose clothing is tucked in. Ensure long hair is tied up.
Backing up data	Loss of data	P	Save data and ensure that multiple backups are stored on different devices.
Turning equipment off	Electrical Shock	P	Momentarily check over cables and wiring to ensure that insulation is thorough. Ensure that power is off before removing cables.
Tidying lab	Tripping	P/E	Be mindful of your surroundings. Do not trip over cables, wires, or knock into the desks. Ensure to be careful when carrying equipment.
	Cuts	P	Beware of sharp corners at workstations/desks.

Leaving Lab	Hand/Body part(s) injuries from the door	P	Ensure all body parts are out the way of the spring-loaded door.

Appendix B Components and Signal Testing

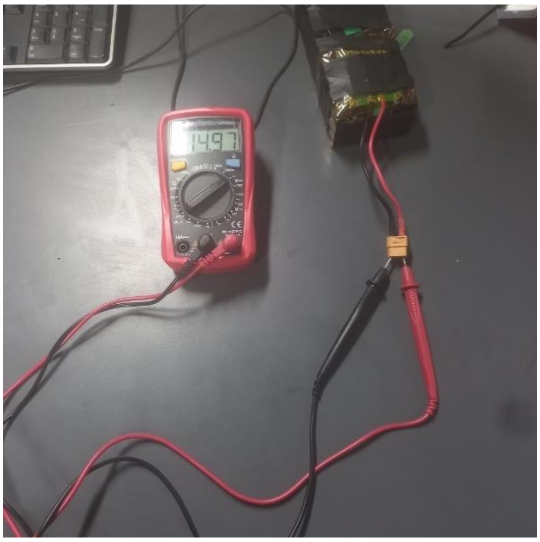

Figure B1: 14V power supply

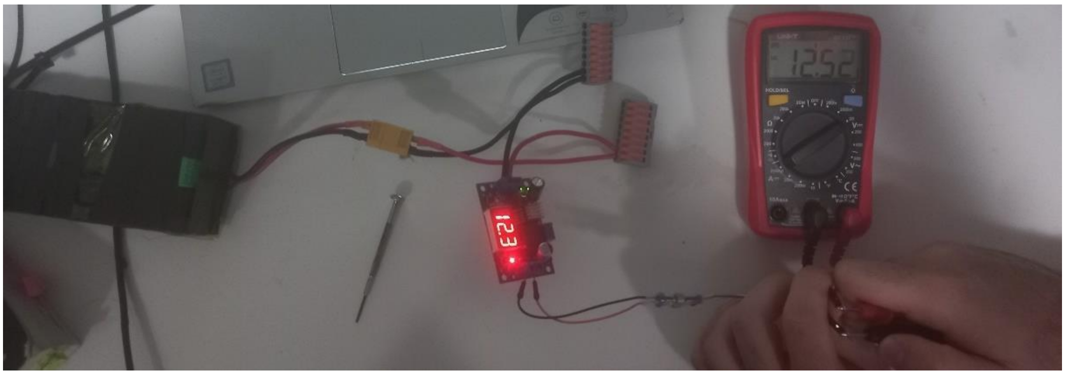

Figure B2: 12V power line

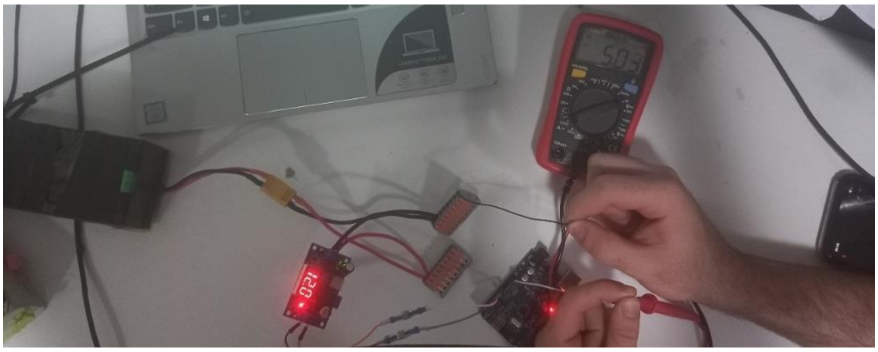

Figure B3: Arduino 5V output pin

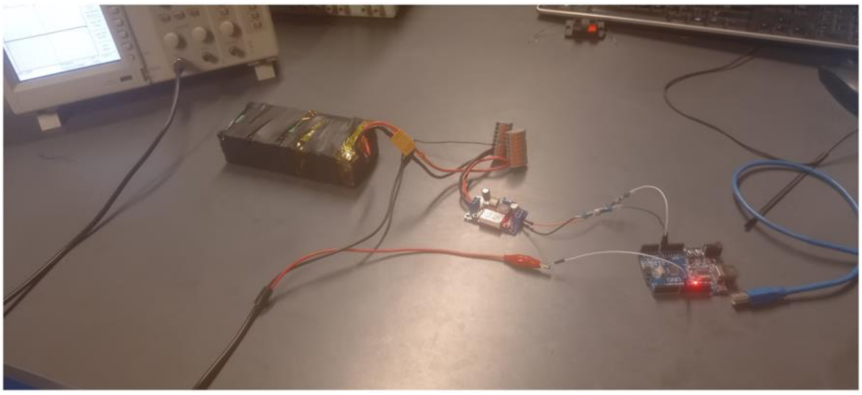

Figure B4: Measurement setup for Arduino thruster pin signals

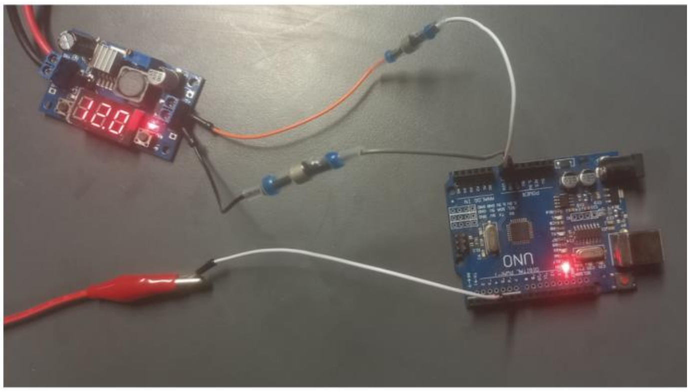

Figure B5: Left thruster pin signal (set at low speed) measurement setup

Figure B6: Left thruster pin oscilloscope PWM signal and peak to peak voltage measurement

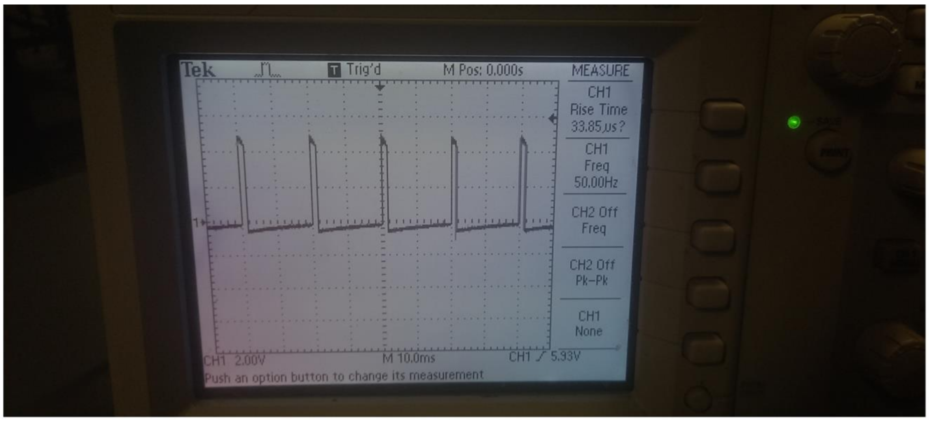

Figure B7: Left thruster pin oscilloscope rise time and frequency measurement

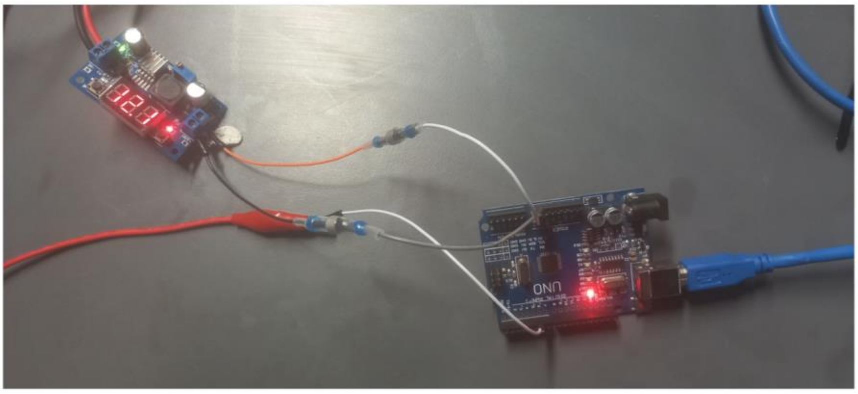

Figure B8: Left thruster pin signal (set at medium speed) measurement setup

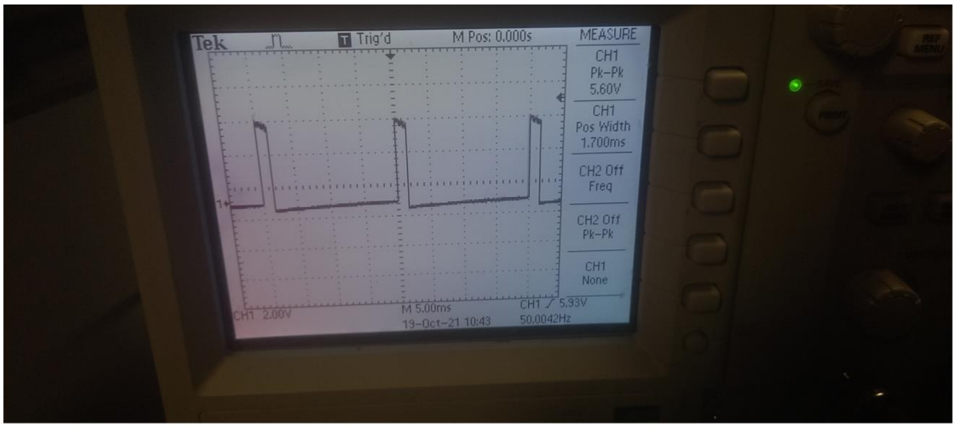

Figure B9: Right thruster pin oscilloscope PWM signal and peak to peak voltage measurement

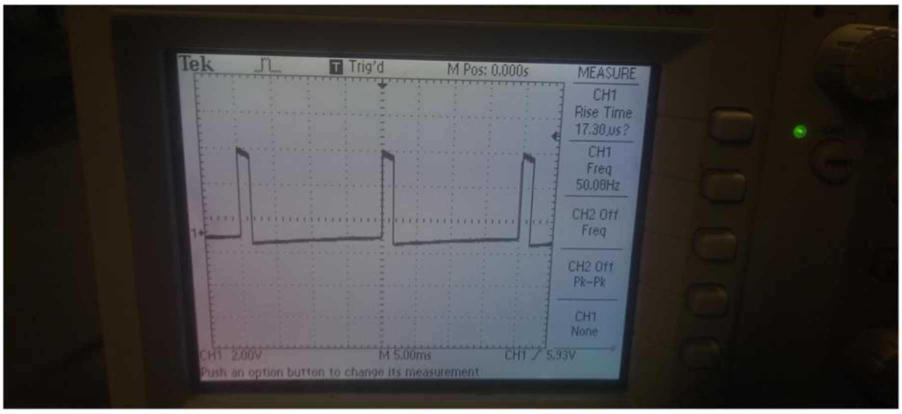

Figure B10: Right thruster pin oscilloscope rise time and frequency measurement

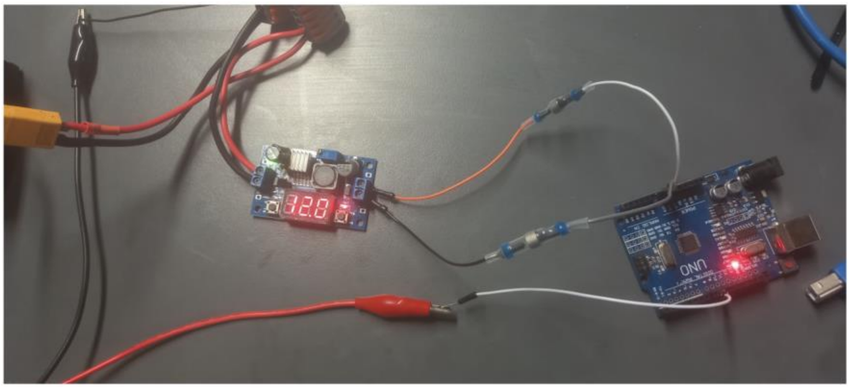

Figure B11: Depth thruster pin signal (set at high speed) measurement setup

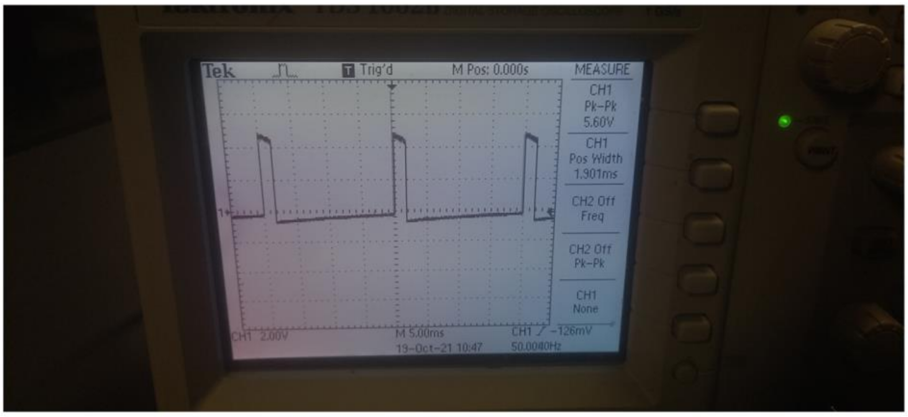

Figure B12: Depth thruster pin oscilloscope PWM signal and peak to peak voltage measurement

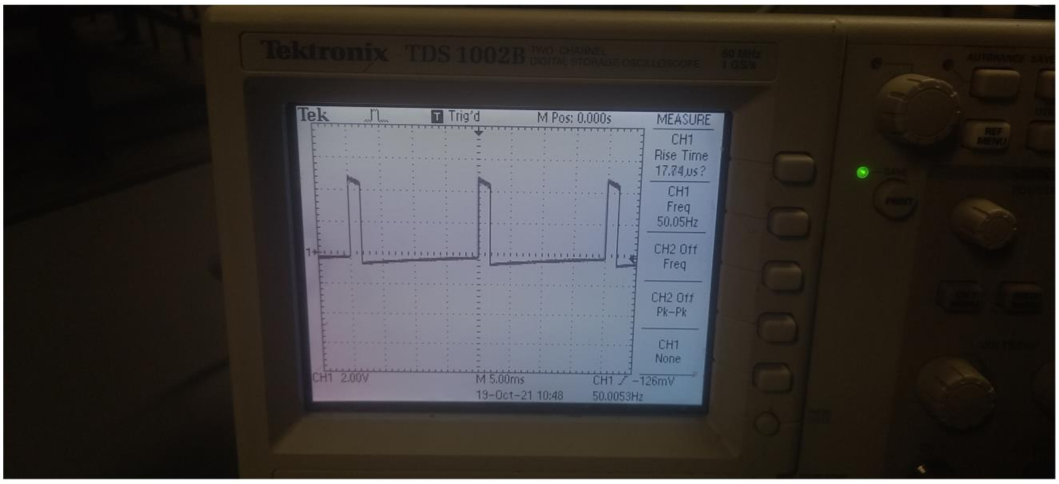

Figure B13: Depth thruster pin oscilloscope rise time and frequency measurement

Appendix C Drawings Pack (3D Prints)

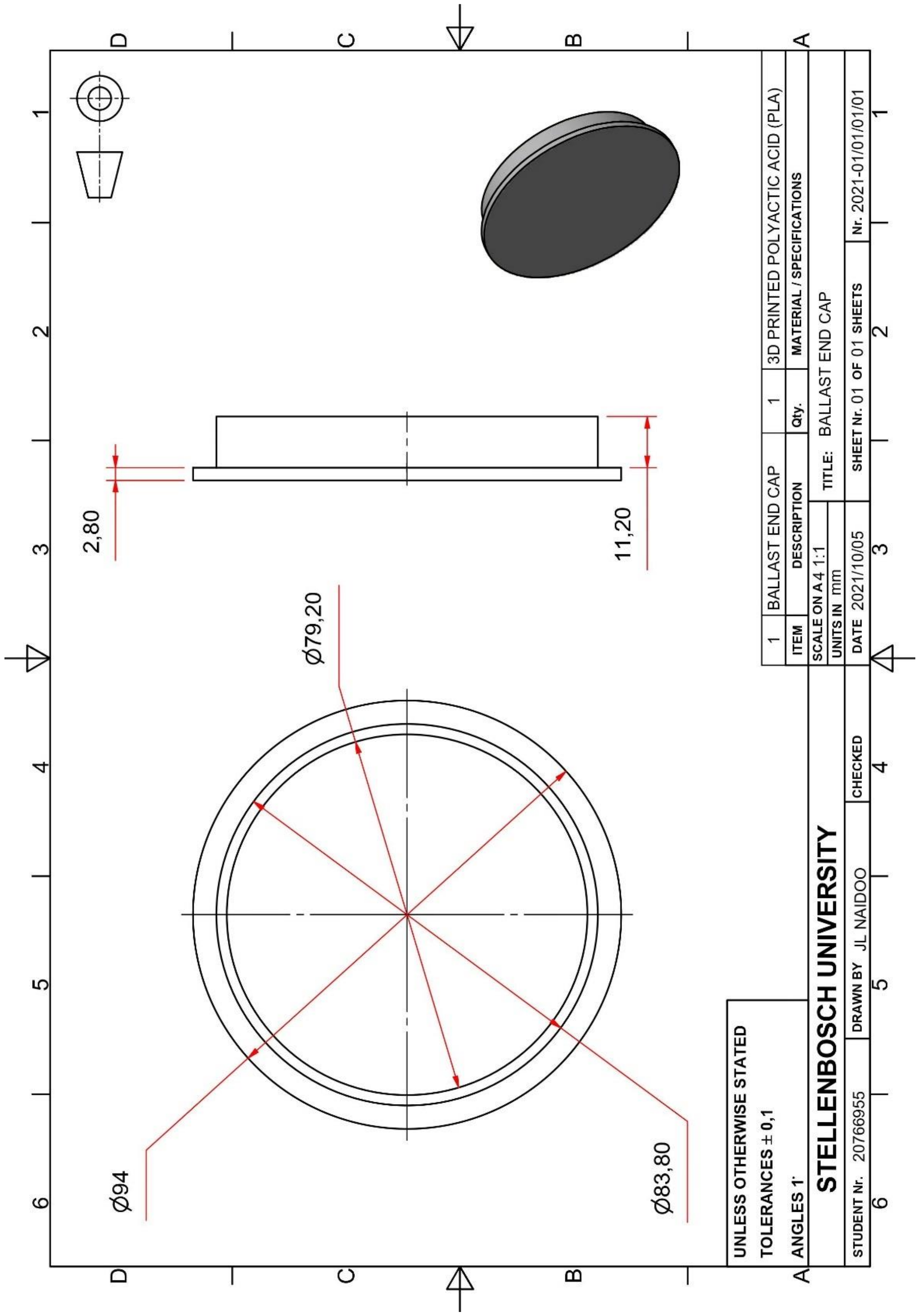

Figure C1: Ballast end cap design

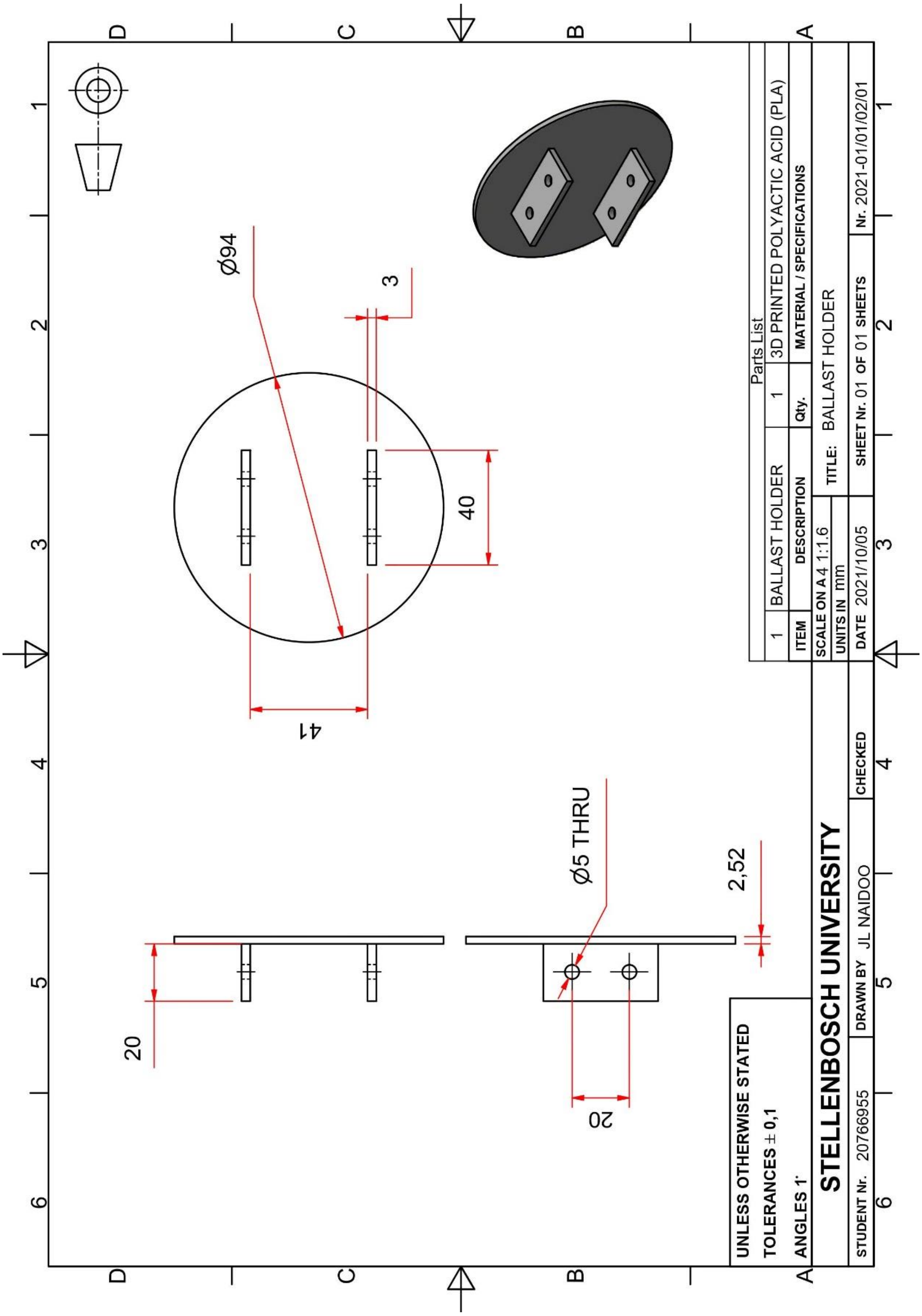

Figure C2: Ballast holder design

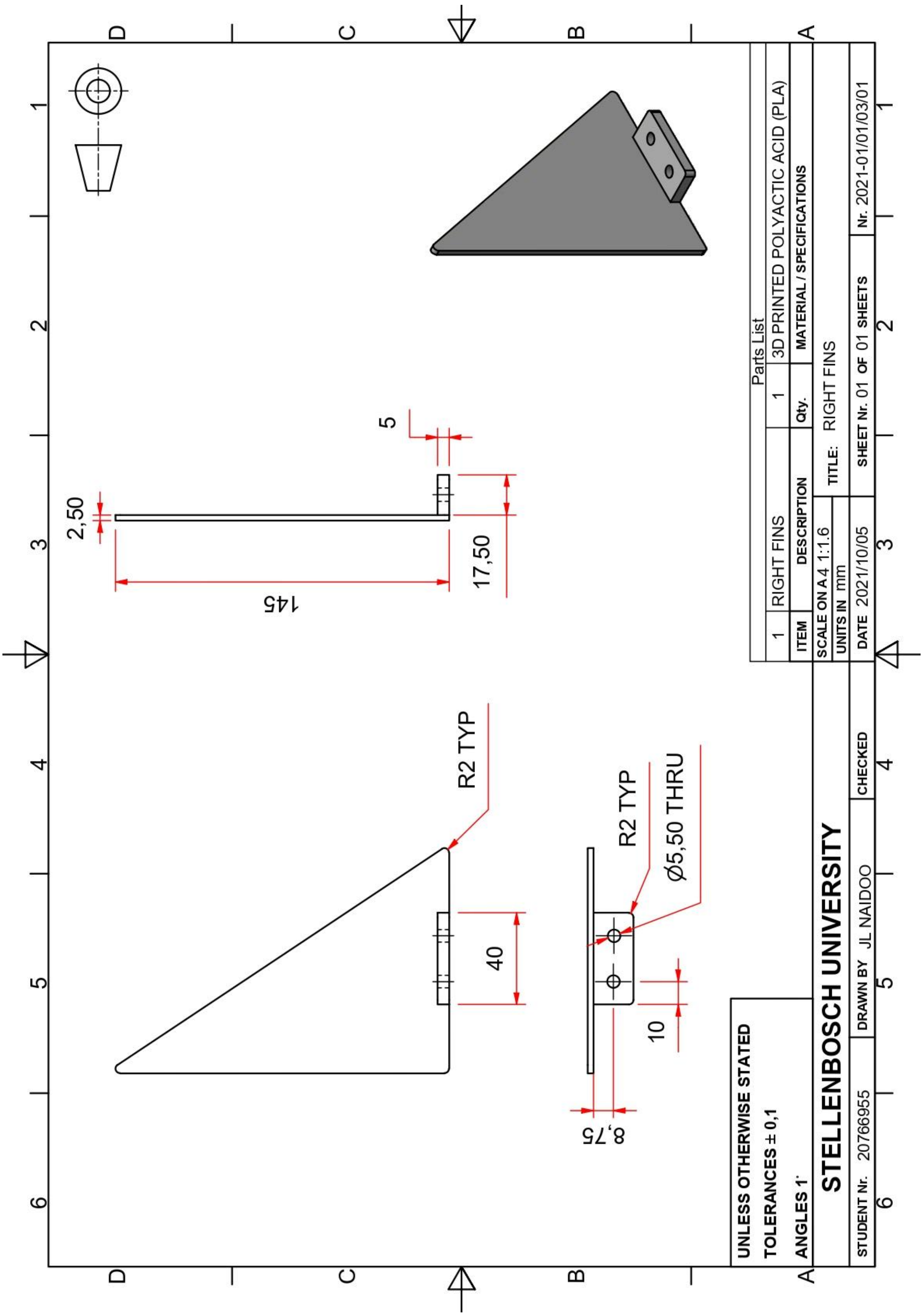

Figure C3: Right fins design

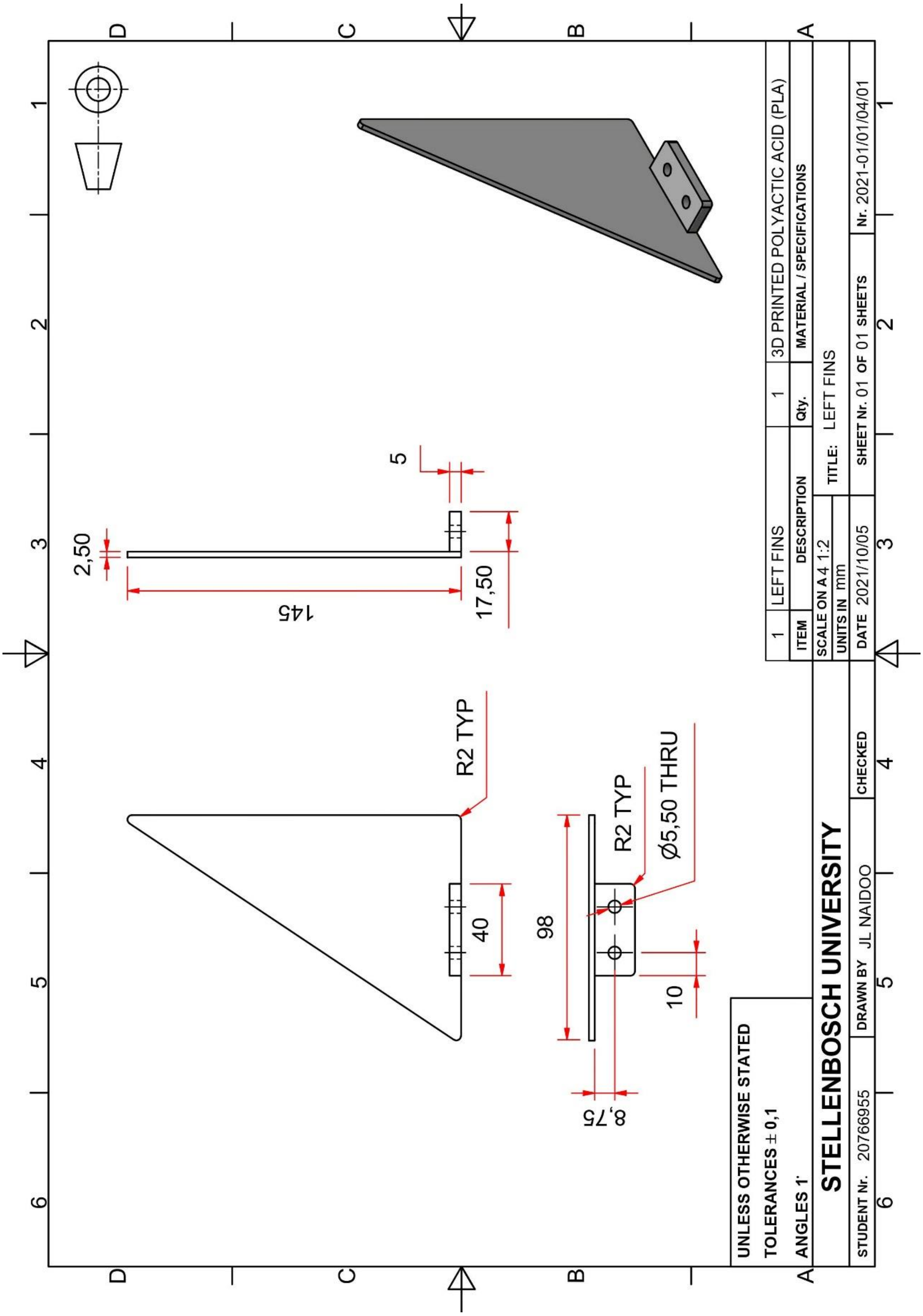

Figure C4: Left fins design

Appendix D Calculations and Code

D.1 AUV Volume Displacement Calculation Code

The code for the AUV volume displacement runs on python and the link is:

https://github.com/jevan-n/AUV_Project/tree/main/Volume_Calculator
(Gazebosim, 2014)

The algorithm uses the initial AUV's prototype dimensions and mass (including all interior components' masses) as an input. The output of the algorithm indicates the total volume of the AUV and the current total weight of the AUV. The code also indicates how much additional mass must be added to the AUV to make it neutrally buoyant. Figure D1 shows that an additional 3.036kg was required to the initial model. Therefore, the total mass of the final AUV prototype is 7.6kg.

VOLUME DISPLACEMENT CALCULATIONS FOR SEA WATER DENSITY = 1023.6 kg/m^3 at 25 degrees C											
	SHAPE	L / (R)	W	H	MASS (kg)	VOLUME (m^3)	BOUYANCY BF (N)	WEIGHT WF (N)	NETT FORCE BF - WF (N)	NEUTRAL NBM (kg)	ADD/SUB MASS (kg)
ALUMINIUM PROFILES (20X40)											
LEFT BEAM	BOX	0.500	0.020	0.040	0.380	0.00040	4.017	3.727	0.290	0.409	0.029
RIGHT BEAM	BOX	0.500	0.020	0.040	0.380	0.00040	4.017	3.727	0.290	0.409	0.029
CROSS BEAM FRONT	BOX	0.250	0.020	0.040	0.195	0.00020	2.008	1.913	0.095	0.205	0.010
CROSS BEAM MIDDLE	BOX	0.250	0.020	0.040	0.195	0.00020	2.008	1.913	0.095	0.205	0.010
CROSS BEAM REAR	BOX	0.250	0.020	0.040	0.195	0.00020	2.008	1.913	0.095	0.205	0.010
THRUSTERS											
LEFT	CYCLINDER	0.040		0.080	0.285	0.00040	4.038	2.796	1.242	0.412	0.127
RIGHT	CYCLINDER	0.040		0.080	0.285	0.00040	4.038	2.796	1.242	0.412	0.127
CENTRE	CYCLINDER	0.040		0.080	0.285	0.00040	4.038	2.796	1.242	0.412	0.127
EC-BOX (ELECTRONICS)											
BOX WITH EC+BATTERY	BOX	0.255	0.175	0.080	1.400	0.00357	35.848	13.734	22.114	3.654	2.254
BALLAST TANK											
MAIN TANK	CYCLINDER	0.047		0.150	0.208	0.00104	10.453	2.036	8.417	1.0655	0.858
SOLENOID VALVE	BOX	0.073	0.050	0.071	0.809	0.00026	2.602	7.936	-5.334	0.2653	-0.544
				TOTAL	**4.617**	**0.0075**	**75.074**	**45.286**	**29.788**	**7.653**	**3.036**

L	length	BF (N)	upward bouyancy force
R	radius	WF (N)	downward force due to gravity
W	width	NMB (kg)	neutral bouyancy mass for the object in sea water
H	height	ADD/SUB	mass to be added or removed from object to achieve neutral bouyancy

Figure D1: Results of AUV Volume Displacement Code

D.2 Arduino Code

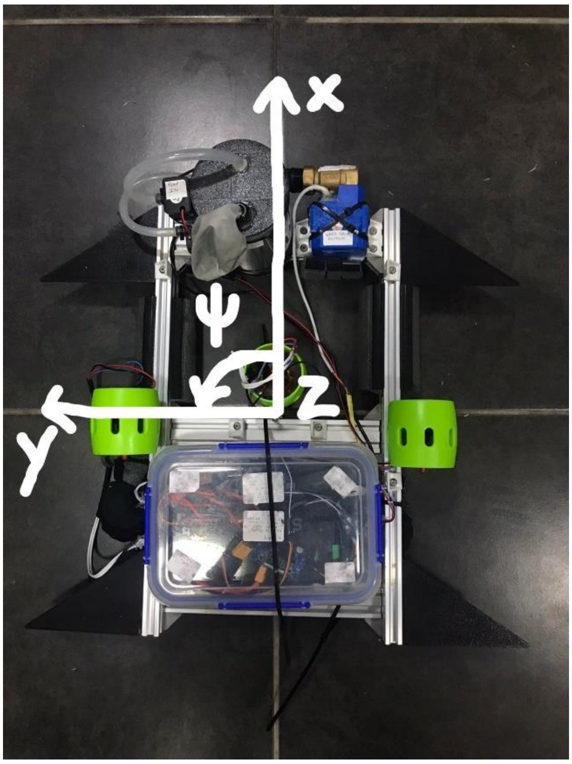

Figure D2: Arduino AUV axes setup

Figure D2 shows the body frame used for the final code and AUV prototype. Note that positive Z is coming out of the page and Ψ is positive anti-clockwise from the X-axis.

D.2.1 Thruster Control System

The thruster control system algorithm used Arduino IDE as the platform and requires an Arduino UNO and a IMU BNO055 to view the code's variables. The algorithm is designed to send the AUV to the set XYZ_{ref} as efficiently and effectively as possible. The control system on Arduino is slightly different to the Simulink model provided in section 6, as it makes use of equations of motion to calculate the XYZ_{act} of the AUV. The XYZ_{ref} can be altered at the start of the code to send the AUV to different coordinates. This is the only way for the user to change the target coordinates of the AUV. The code is explained further in depth by use of comments within the code. The comments allow for the user to understand how the AUV sequentially manoeuvres to its target position. The AUVs thruster control system code link is:

https://github.com/jevan-n/AUV_Project/blob/main/Arduino_Code/Ardunio_AUV_Controller_V6.ino

D.2.2 Ballast Tank Control System

The ballast control system algorithm is also written on Arduino IDE. This code only requires an Arduino Uno to view the desired variables of the control system. Unfortunately, due to the project budget a depth pressure sensor could not be incorporated to aid this control system. Instead, the algorithm is already injected with a disturbance from the Z_{ref} by setting Z_{act} to 0.5m above its target depth position. The code then uses the mass flowrate of the pumps (either for in/out) and the pump's running time to determine the net mass change for the AUV. Using the mass an equation can then be used to determine the change in Z_{act} (depth) of the AUV. The code stops once $Z_{act} = Z_{ref}$, allowing for the vehicle to stabilize at a specific without the use of any thrusters. The algorithm for the control system is explained in more detail with comments in the code. The link for the ballast tank control system is:

https://github.com/jevan-n/AUV_Project/blob/main/Arduino_Code/Arduino_AUV_Ballast_v2.ino

D.3 Simulink Models

The Simulink models run on MATLAB 2021a. The link for all Simulink/MATLAB models used in section 6 and 7 is:

https://github.com/jevan-n/AUV_Project/tree/main/Simulink_Model

Appendix E Techno-Economic Analysis

The techno-economic analysis is presented in this appendix where the technical and economic influence of the project is examined. Considerations include the budget, planning and execution of the project, technical impact, return on investment and lastly the potential for commercialization.

E.1 Budget

Tables E1 and E2 shows a difference between the budget for the project proposal and actual cost at the end of the project. Tables E1 and E2 also depicts the comparison between the estimated parts cost and the actual parts cost at project completion. Figure E1 below shows the comparison of the labour cost for the project proposal against the actual labour cost at project completion.

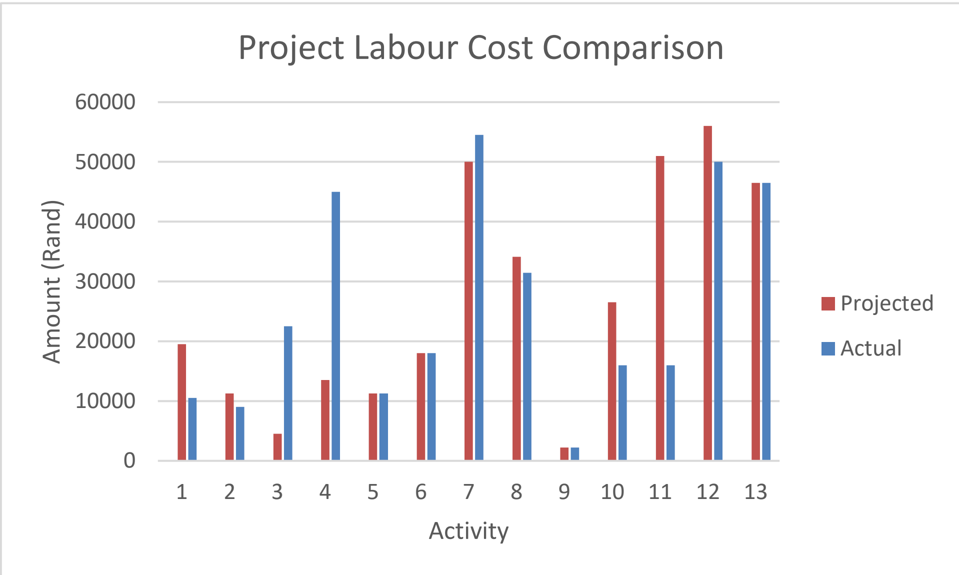

Figure E1: Comparison between the projected labour cost and actual labour cost of the project

From the tables below it can be determined that the actual budget (including labour cost) is R31 416.80 less than the proposed budget. It can also be concluded that the actual parts cost is R19966.80 (including VAT) less than the proposed. Using figure E1 the biggest difference in labour costs occurred with the propulsion and kinematics model activity. The actual cost of this activity proved to be more than initially scheduled. This was due to an increase in the required engineering hours needed to complete the activity being underestimated.

Table E1: Proposed budget for the project

ACTIVITY	ENGINEERING TIME		RUNNING COSTS	FACILITY USE	CAPITAL COST	MMW LABOUR		MMW MATERIAL	TOTAL
	HOURS	ZAR	ZAR	ZAR	ZAR	HOURS	ZAR	ZAR	ZAR
1. Research Literature	40	18,000	1,500						19,500
2. Research Systems Design Platforms	25	11,250							11,250
3. Systems Architecture Design	10	4,500							4,500
4. Propulsion & Kinematics Model	30	13,500							13,500
5. Ballast Options	25	11,250							11,250
6. Autonomous Motion Algorithms	40	18,000							18,000
7. Design Simulated Model	100	45,000		5,000					50,000
8. Select Preferred Design	16	7,200			26,950				34,150
9. Design Review	5	2,250							2,250
10. Design Concept Demonstrator	50	22,500		2,500		5	1,500		26,500
11. Mnfr Concept Demonstrator	30	13,500	2,500			100	30,000	5,000	51,000
12. Test & Validate Demonstrator	100	45,000		5,000		20	6,000		56,000
13. Compile Final Report	100	45,000	1,500						46,500
TOTAL	**571**	**256,950**	**5,500**	**12,500**	**26,950**	**125**	**37,500**	**5,000**	**344,400**

PARTS ESTIMATE (BLUE ROBOTICS PRICING)			
Thrusters	3	179	537
Speed Controllers	3	27	81
3 Series Enclosure with End Caps	2	184	368
Depth & Pressure with PCB	1	130	130
Battery Pack	1	289	289
Rasp Pi 4	1	100	100
Micorcontroller (Arduino)	1	25	25
TOTAL USD			1,530
TOTAL ZAR			22,950
Aluminium frame	2	500	1,000
Ballast	2	1,500	3,000
TOTAL ZAR			26,950

Table E2: Actual budget for the project

ACTIVITY	ENGINEERING TIME		RUNNING COSTS	FACILITY USE	CAPITAL COST	MMW LABOUR		MMW MATERIAL	TOTAL
	HOURS	ZAR	ZAR	ZAR	ZAR	HOURS	ZAR	ZAR	ZAR
1. Research Literature	20	9,000	1,500						10,500
2. Research Systems Design Platforms	20	9,000							9,000
3. Systems Architecture Design	50	22,500							22,500
4. Propulsion & Kinematics Model	100	45,000							45,000
5. Ballast Options	25	11,250							11,250
6. Autonomous Motion Algorithms	40	18,000							18,000
7. Design Simulated Model	110	49,500		5,000					54,500
8. Select Preferred Design	10	4,500			26,950				31,450
9. Design Review	5	2,250							2,250
10. Design Concept Demonstrator	30	13,500		2,500		0	0		16,000
11. Mnfr Concept Demonstrator	30	13,500	2,500			0	0	0	16,000
12. Test & Validate Demonstrator	100	45,000		5,000		0	0		50,000
13. Compile Final Report	100	45,000	1,500						46,500
TOTAL	**640**	**288,000**	**5,500**	**12,500**	**26,950**	**0**	**0**	**0**	**332,950**

ACTUAL PARTS COST	Units	Price/Unit ZAR	Subtotal ZAR
Aluminuim Profiles (20x40)	2	170.00	340.00
Angle Connectors (90 degree)	12	15.00	180.00
M5x8mm Hex Screws (10x5pcs)	10	10.00	100.00
M5 T-nuts	10	15.00	150.00
Thrusters	3	310.00	930.00
Electronic Speed Controllers	3	185.00	555.00
Angle Brack Mountings	3	26.00	78.00
Screws (Self Threading)	6	0.70	4.20
Air-tight Enclosure 2.2L	1	140.00	140.00
Arduino Uno	1	158.00	158.00
DC Buck Converter (5V Supply)	1	155.00	155.00
Lithium Ion Battery (Battery Pack)	16	79.00	1,264.00
BMS 4S Battery Charging Module	1	148.00	148.00
IMU BNO055	1	890.00	890.00
Acrylic Tube (90mmx150mm)	1	120.00	120.00
Solenoid Valve	1	470.00	470.00
12V Submersible Pumps	2	180.00	360.00
2 Channel Relay	2	55.00	110.00
Rubber Balloon	1	2.00	2.00
Electrical Wires 22-awg (multi colour)	2	79.00	158.00
Electrical Wires 18-awg (20A max)	1	51.00	51.00
Electrical Connectors	1	20.00	20.00
Waterproof Cable Connector	1	349.00	349.00
3-D Print (Fins and Ballast Covers)	10	15.00	150.00
Cable Ties	1	49.00	49.00
Marine Silicone Sealant	1	52.00	52.00
TOTAL ZAR			6,983.20

Note prices may have fluctuated from suppliers.

E.2 Planning

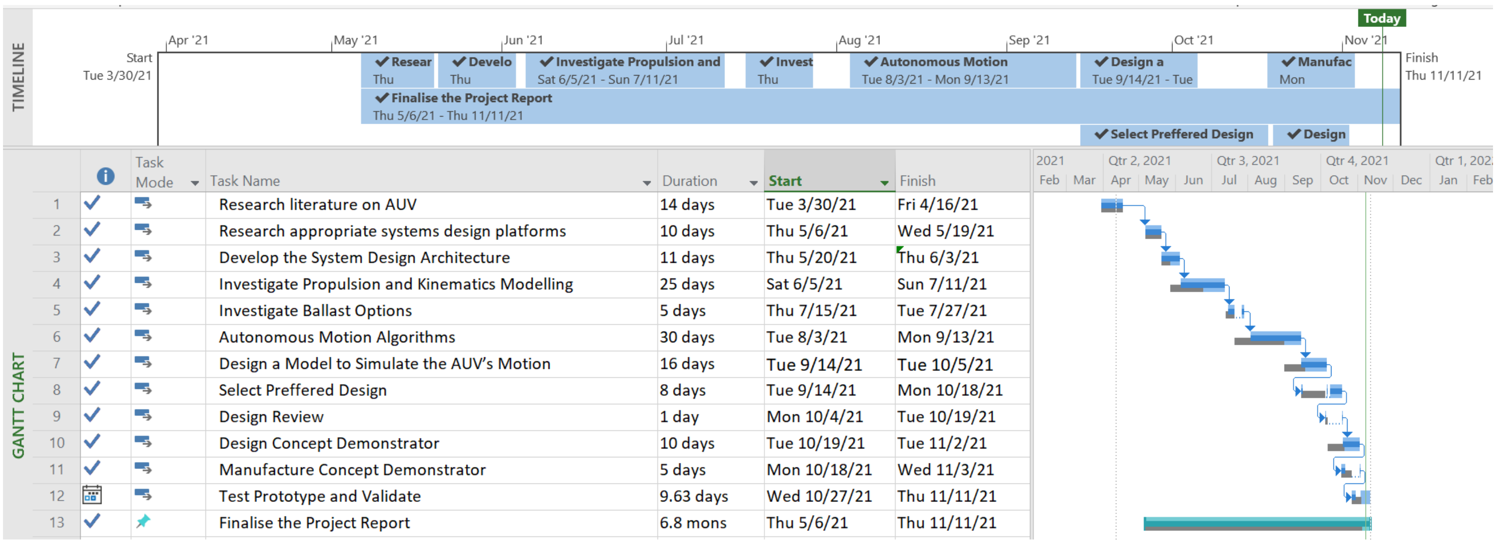

Figure E2: Gantt chart comparing the baseline timeline to the actual timeline

Figure E2 shows a comparison between the baseline timeline of the project proposal and the actual time for project completion. The last task seems to depict that the project was completed after the due date. This is not true as the initial plan did not take into account that the hand-in date was extended by a week. The initial plan was working until activity 3 and 4. Developing the system architecture and investigating the kinematics models were the first tasks that took longer than scheduled. This led to a domino effect of delays over the other tasks. These delays caused certain tasks to start while others were incomplete. In other words, some activities were required to be completed in parallel. This allowed for the project to completed by the new deadline.

As a result, activity 12 was only partially completed within the given time frame. Fortunately, the report could still be finalised and submitted without the completion of activity 12. The delays did increase particular costs of the project. However, due to the extension and significant reduction to the budget for components allowed for the project to finish under budget.

E.3 Technical Impact

Underwater maintenance, exploration and data acquisition can be costly and time-consuming to conduct. Therefore, there is a clear need to create AUVs that efficiently complete these objectives. The design and implementation of the control systems for the AUV in this project have a successful input in how the AUV complete underwater missions. However, the build and testing of the AUV did fail due to the use of inexpensive components. When a bigger budget is available, modifications can be made to further optimize the real-life testing of the AUV.

The project justified the financial input since feasible control systems were designed and implemented onto a microcontroller which can be of use to many AUVs to help in the discussed market mentioned section 2.3.

E.4 Return on Investment

As mentioned in section 2.3 there are countless applications for an AUV in a variety of industries. The market for the AUV will forever increase as the world shifts towards the use of autonomous vehicles. Leading to a demand for autonomous underwater missions and exploration to be completed. This demand requires to be met with a constant adequate supply.

An autonomous underwater vehicle's control system was designed and implemented in this project to meet parts of the demand. Further research into developing the autonomous underwater vehicle to meet more of the demands will be advantageous to the investors and market. This could be a possible next step of this project for future Mechatronic Project 478 students to follow.

E.5 Potential for Commercialization

Refer to section 2.3 for commercial applications of an AUV. For this projects AUV to possibly become a commercial product. It would require a higher budget for higher quality components. Possibly an increase in the number of thrusters used in order to control additional degrees of freedom. Refer to section 9 to see additional recommendations that will aid this project's commercial viability.

Appendix F Final Prototype

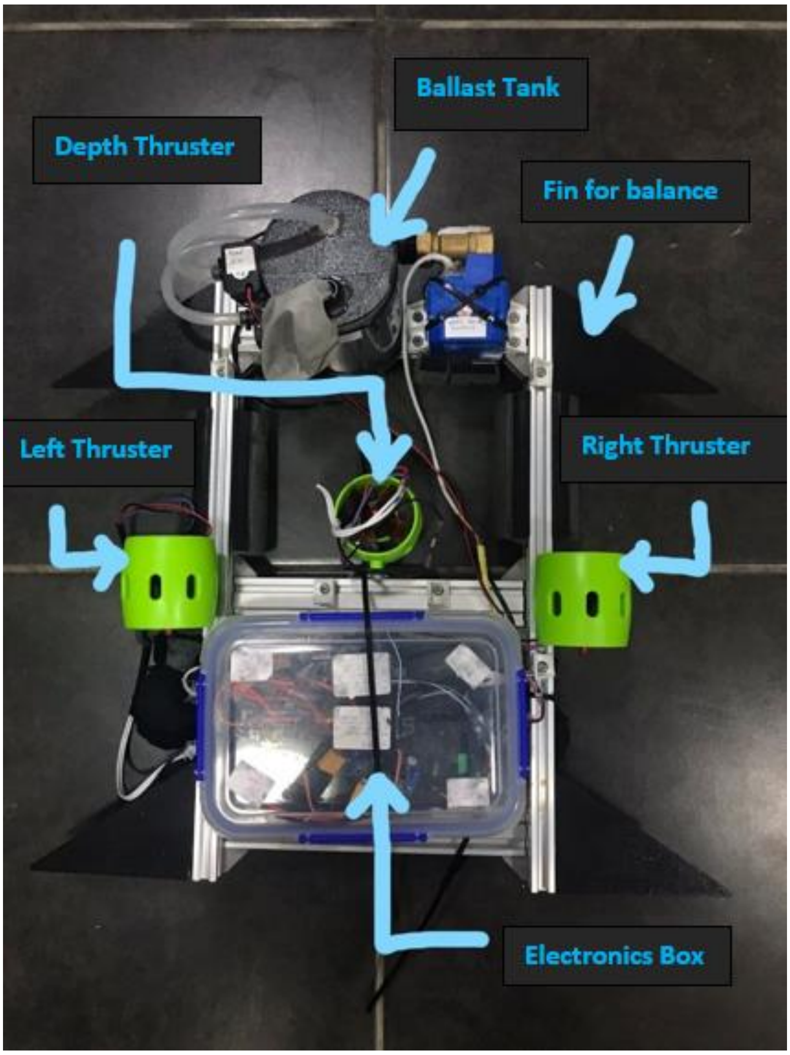

Figure F1: Top view of final prototype with labels

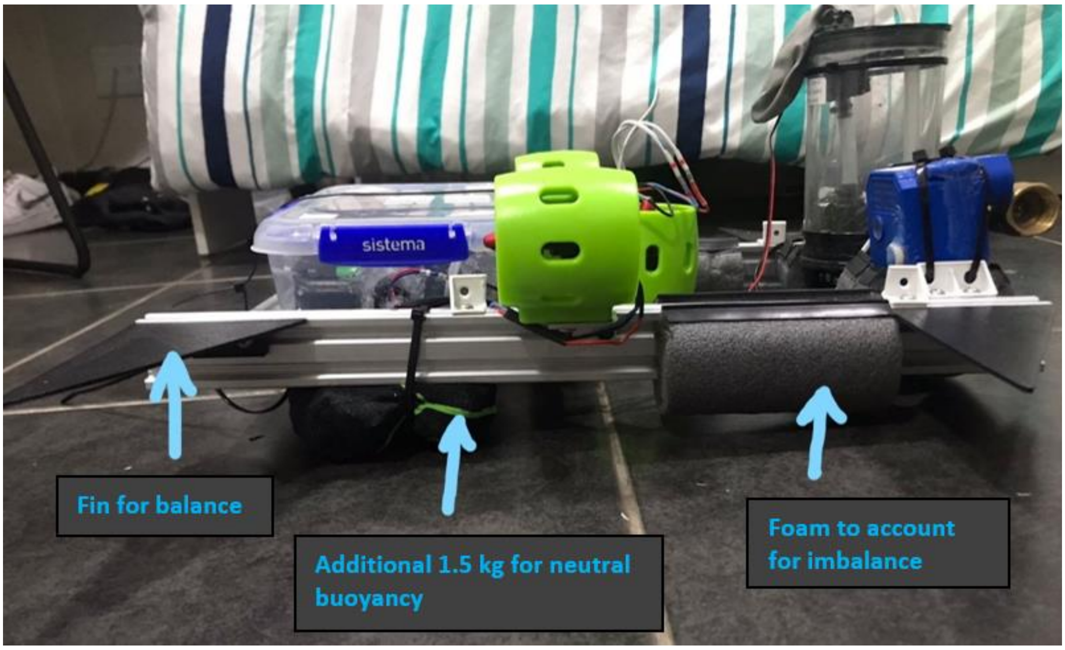

Figure F2: Right view of final prototype with labels

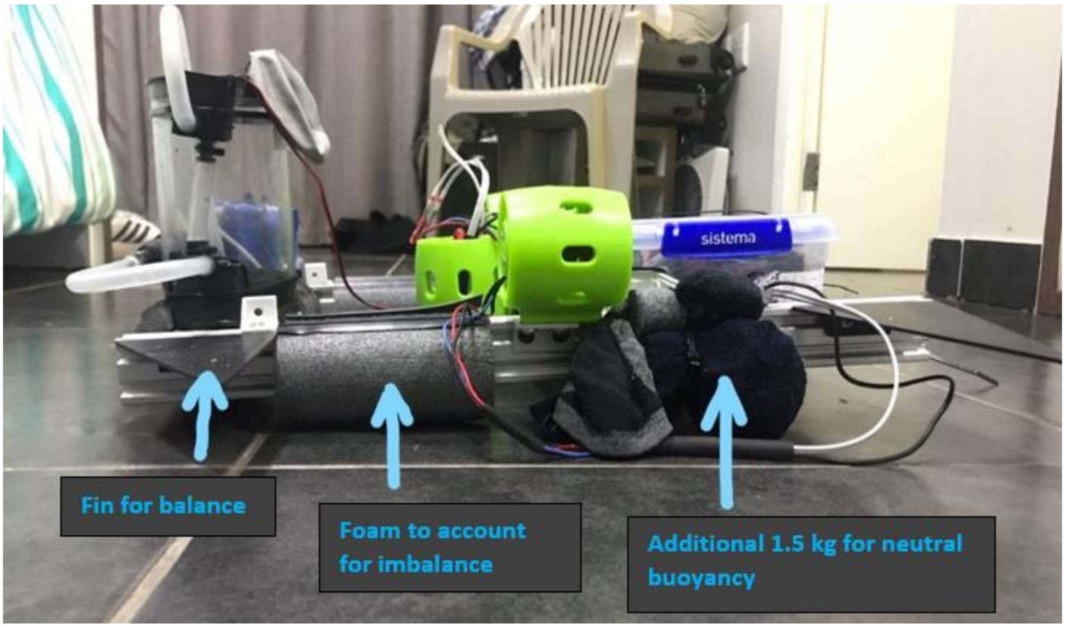

Figure F3: Left view of final prototype with labels

Figure F2 and F3 show where the additional 3kgs required for the AUV to become neutrally buoyant was incorporated (mentioned in appendix D.1).

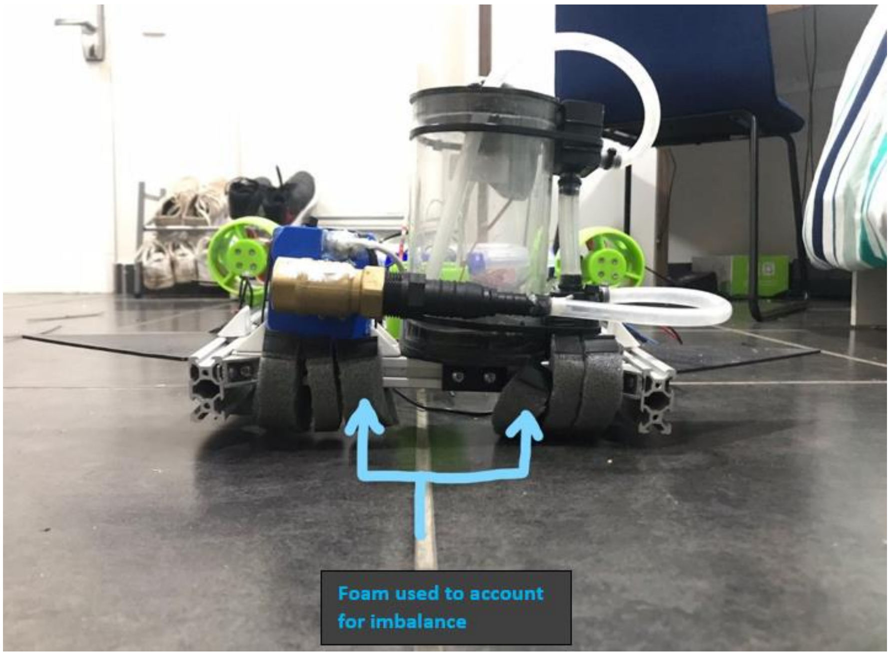

Figure F4: Front view of final prototype with label

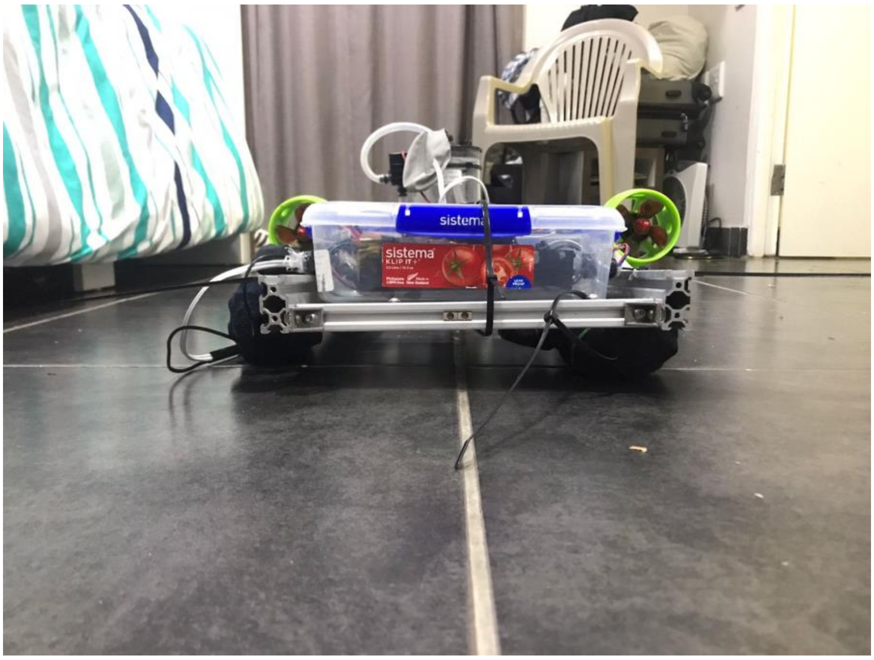

Figure F5: Back view of final prototype

Appendix G Components List

Table G1: Component list with links to supplier

	QTY	SUPPLIER - click link to view part and specifications
BASE STRUCTURE		
Aluminium Profiles (20x40)	1	3D Printing Store (Centurion) Sold by meter (cut 2 x 500mm)
Aluminium Profiles (20x40)	1	3D Printing Store (Centurion) Sold by meter (cut 4 x 250mm)
Angle connectors (90 degree)	12	3D Printing Store (Centurion)
M5x8mm hex screws (10x 5pcs)	10	3D Printing Store (Centurion) - sold in packs of 5
M5 T-nuts	10	3D Printing Store (Centurion) - sold in packs of 5
THRUSTERS		-
Bi-directional RC boat	3	Bangood - Thrusters
ESC speed controller (20/30A)	3	Bangood - ESC 30A
Angle brackets mounting	3	3D Printing Store (Centurion) - mount thrusters to aluminium profile
Washers spacers (5mm)	12	included with M5x8mm hex screws (above)
Screws (self-threading)	**6**	Builders Warehouse - Self Tapping Screws 5x16mm
ELECTRONICS BOX		-
Air-tight enclosure 2.2l	1	Dischem - Sistema 2.2lt airtight container
Arduino Uno	1	Microrobotics - Stellenbosch
DC Buck Converter (5v supply)	1	Microrobotics - Stellenbosch

18650 Li-Ion Battery 10000mAh	16	Boss Vape - Samsung 25R 18650 3.7v 2500mAh - 4s4p 14.8v
BMS 4S battery charging module	**1**	Botshop.co.za - BMS 4s 18650 charger
IMU BNO055	1	Microrobotics - Stellenbosch
BALLAST TANK		-
Acrylic Tube 90mmx150mm	1	PlasticWorld.co.za - can request cut to size
Solenoid Valve	1	DiYElectronics.co.za - DN20 Solenoid Valve
Pumps 12dc	**2**	DiYElectronics.co.za - DN20 Solenoid Valve
Relays 12v (dual module)	2	DiYElectronics.co.za - 2-Channel 5V relays 5 amp
Rubber balloon	1	Any party shop
MISCELLANEOUS		-
Electrical wires 22-awg (multi colour))	2	Microrobotics - Stellenbosch - 22awg 5-way 5m control wire cable
Electrical wires 18-awg (20A max)	1	Microrobotics Stellenbosch - Red-Black 20A 18awg 5m cable
Electrical connectors	1	Microrobotics Stellenbosch - 4 pack - used for 5v, 12v and 0v bus-bar
Waterproof cable connector	1	Takealot - pack of 5 - used to feed cables into electronics control box
3-D Print (Fins and Ballast Covers)	10	DIY design on CAD and printed with PLA (250g PLA used for all 10 prints)
Cable ties (pack of 100)	1	Builders Warehouse - 4.8x200mm - secure components to structure
Marine Silicone sealant	1	Builders Warehouse - waterproof cable penetration into electronics box